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The aerodynamic properties of an airfoil under unsteady conditions are very different from the ones in steady conditions because the vortex generated by unsteady separation greatly modifies the loading on the wing. In ~~the present~~ study, a fundamental approach was taken to investigate the lift and the velocity field of unsteady airfoils.

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"Control of Unsteady Aerodynamic Forces"

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CONTROL OF UNSTEADY AERODYNAMIC FORCES

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ABSTRACT

The aerodynamic properties of an airfoil under unsteady conditions are very different from the ones in steady conditions because the vortex generated by unsteady separation greatly modifies the loading on the wing. In the present study, a fundamental approach was taken to investigate the lift and the velocity field of unsteady airfoils.

ACCOMPLISHMENTS

The findings are briefly summarized in this report. The details are available in the attached papers or in the Publication List at the end of the report.

Unsteady Water Channel

A proto-type vertical water channel was built to provide various unsteady free stream conditions for the tested airfoil. The water channel has a very simple design, but can offer very versatile operating conditions. Based on our past experiences, we built a new water channel that has a test section four times larger and with a flow rate ten times higher. It is in working condition now. The same design has been copied by many research institutes in this country and abroad.

Vorticity Balance of a 2-D Airfoil

Based upon the fundamental vorticity balance concept, we are able to understand the lift variations of a 2-D airfoil under sinusoidally varied free stream. When the airfoil is not separated, the time-varying flow has one external time scale which is the free stream velocity period. The lift is totally determined by the vorticity diffused from the surface. In the separated phase, the aerodynamic forces are functions of several time scales, separation, vortex formation, convection time scales and

free stream velocity period. The effect of vorticity convection dominates the influence of vorticity diffusion.

An Airfoil with C_L 10

(Ref. Ho, Gursul, Shih and Lin 1990)

Using our understanding from the vorticity balance, we found that an unsteady 2D airfoil has a preferred reduced frequency. In the unsteady free stream at this preferred frequency, the time averaged lift coefficient has a maximum value. Furthermore, the maximum lift coefficient increases with increasing free stream velocity amplitude. In the present water channel, we can find an operating condition such that the phase averaged lift coefficient can reach 15 in an appreciable duration of the cycle.

Numerical Study of the High Lift Coefficient Airfoil

A time accurate Navier-Stokes code was applied to calculate the lift coefficient of a NACA 0012 airfoil in a sinusoidally varied free stream. The angle of attack is in the post-stall region. The time series of the lift coefficient was calculated. The numerical result was compared with the experimental data. The agreement was excellent.

An Extensive Review of the Delta Wing Studies

(Ref. Lee and Ho 1990)

The aerodynamics of delta wing has been an active research area during the past few decades, but no comprehensive review based on fundamental fluid mechanics concept is available. In this survey article, we reviewed the papers on steady and unsteady delta wings based on the vorticity balance concept.

Lift Measurements and Flow Visualization of the Delta Wing

The lifts of delta wings with different aspect ratio were measured. The frequency and the amplitude of the free stream velocity were varied. The lift does not depend on the frequency, but is a sensitive function of the amplitude of the velocity variations.

Flow visualization was carried out by illuminating the air bubbles with a thin sheet of laser light. The behaviour of the leading separation vortex was examined in a wide range of operating parameters. The vortex breakdown position and the convection speed of the breakdown point were documented for various flow conditions.

KEYNOTE TALKS IN CONFERENCES

1. "Control of Entrainment and Small Scale Mixing", AIAA Second Shear Flow Control Conference, Tempe, AZ, March 13-16, 1989.

2. "Concepts of Mixing Control", NASA Turbulence Workshop, Stanford, CA, June 27 - July 22, 1988.

PH.D. THESIS

1. Unsteady Aerodynamics of a Stationary Airfoil in a Periodically-varying Free-Stream by Chiang Shih, Aug., 1988.

PUBLICATIONS

1. "Vortex Dynamics of Delta Wings", with Lee, M., Lecture Notes in Engineering, Vol. 46, pp. 365-433, 1989.

2. "Vorticity Balance on 2-D and 3-D Unsteady Airfoils", with Gursul, I., Shih, C. and Lin, H. to appear in NASA TM 1990.

3. "Unsteady Free-stream Effects on a Stationary 2-D Airfoil", with Shih, C., Bulletin of the American Physical Society, Vol. 33, p. 2252, 1988.

4. "Experiments on Two- and Three-Dimensional Lifting Surfaces in an Unsteady Free Stream", with Gursul, I., Bulletin of American Physical Society, Vol. 34, p. 2307, 1989.

To appear in NASA TM.

UNSTEADY SEPARATION PROCESS AND VORTICITY BALANCE ON UNSTEADY AIRFOILS

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ABSTRACT

Low momentum fluid erupts at the unsteady separation region and forms a local shear layer at the viscous-inviscid interface. At the shear layer, the vorticity lumps into a vortex and protrudes into the inviscid region. This process initiates the separation process. The response of airfoils in unsteady free stream was investigated based on this vortex generation and convection concept. This approach enabled us to understand the complicated unsteady aerodynamics from a fundamental point of view.

INTRODUCTION

Unsteady separation is an important feature of many flows. For example, when an airfoil undergoes maneuvering, the lift and drag experience very large variations from the steady state values. The unsteady separation from the leading edge produces coherent vortical structures which can greatly alter the surface loading on the wing (McCrosky, 1982). The separation process and the formation of the vortices can be very different for various operating conditions. On a 2D airfoil, there is no effective vorticity convection mechanism. The separating vortices therefore can not hold on to the chord and are convected by the mean flow. Shih (1988) found that the time needed for the vortex moving along the chord is an important time scale in determining the aerodynamic properties. On a small aspect ratio delta wing, vorticity can be transported along the cores of the leading edge separation vortices. The vortices can be stationary on the wing. Therefore, there is no vortex convection time scale. In this paper, the measured lift of airfoils in an unsteady free stream will be presented and will be interpreted by the vorticity balance concept (Reynolds and Carr, 1985).

1. UNSTEADY SEPARATION MECHANISM

It has been experimentally shown that shear stress vanishes at an interior point away from the wall for both upstream moving separation (Shih, 1988) and downstream moving

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separation (Didden and Ho, 1985). These cases were illustrated in figures 1a and 1b. The data validated the MRS criterion and showed many important aspects of unsteady separation pointed out by Van Dommelen and Shen (1982). Erruption of the boundary layer fluid and the formation of a local shear layer with an inflection point (figure 2) was found to be generic to unsteady separation.

When an external disturbance induces an unsteady adverse pressure gradient (figure 3), the fluid particles near the wall decelerates. Low momentum fluid errupts from the wall region. A local shear layer forms at the boundary of the inviscid and viscous zones. Velocity profile of the local shear layer has an inflectional point between the point $\partial u/\partial y = 0$ near the wall and $\partial u/\partial y = 0$ at free stream. This shear layer is inviscidly unstable and extracts energy from the mean flow.

2. UNSTEADY WATER CHANNEL

Experiments on unsteady airfoils were performed in an unsteady water tunnel (figure 4). The tunnel was operated under constant head. Therefore, the free stream speed was determined by the resistance provided by the exit gate. This arrangement made the tunnel extremely versatile and simple to operate. The opening area of the exit gate was controlled by a computer-driven stepping motor. The free stream velocity was varied as a function of time in many different types of waveforms. The lift was measured by load cells while the velocity field was measured by laser Doppler velocimetry.

3. ATTACHED UNSTEADY FLOW AROUND 2D AIRFOIL

When the flow on the 2D airfoil was attached, the vorticity convection was balanced by a part of the vorticity diffusion. Hence, the convected vorticity did not play a role in the dynamics. The lift was determined by the rest of the vorticity diffused from the surface. Since there was no intrinsic time scale of the vorticity balance, the lift curves of the attached flow was only scaled by the free stream velocity time scale. Based upon the vorticity balance we can show that the local circulation is scaled with the velocity at the edge of the boundary layer.

4. SEPARATED UNSTEADY FLOW AROUND 2D AIRFOIL

During the separated phase, the vorticity measurement indicated that the vorticity diffused from the surface is negligible compared with that shed from the leading edge. In other words, the flow was controlled by the vorticity convection instead of the vorticity diffusion. The vorticity originating from the leading edge rolled up into a vortex which produced high suction on the wing. When this lift generating vortex moved from leading edge to trailing edge, the lift of the unsteady airfoil was much higher than that of the steady one. The lift dropped significantly after the lift generating vortex left the chord. Therefore, the ratio between the vortex convection time scale and external perturbation time scale dictates the lift curve of the airfoil.

5. AN AIRFOIL WITH $C_L > 10$

How to obtain high lift coefficient in the post stall region is the goal of supermaneuverability research. The fundamental understanding of the time scale and the vorticity balance on the separated airfoil mentioned in the above section enabled us to achieve this purpose. We placed a NACA 0012 airfoil at an angle of attack of 20° which is in the static stall region. The reduced frequency was chosen such that a large coherent vortex can be trapped on the chord for an appreciable portion, say 40%, of the cycle. We then obtained a lift coefficient larger than ten. This is shown in figure 5.

ACKNOWLEDGMENT

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REFERENCES

Didden, N. and Ho, C.-M., 1985, "Unsteady separation in a boundary layer produced by an impinging jet", *J. Fluid Mechanics*, Vol. 160, pp. 235–256.

McCrosky, W. J., 1982, "Unsteady Airfoils", *Annual Rev. Fluid Mech.*, Vol. 14, p. 285.

Reynolds, W. C. and Carr, L. W., 1985, "Review of Unsteady, Driven, Separated Flows", AIAA Paper No. 850527.

Shih, C., 1988, "Unsteady Aerodynamics of a Stationary Airfoil in a Periodically Varying Free Steam", USC Ph.D. Thesis.

Van Dommelen, L. L. and Shen, S. F., 1982, The genesis of separation. In *Numerical and Physical Aspects of Aerodynamic Flows* (ed. T. Cebeci), pp. 293–311, Springer.

Upstream moving separation

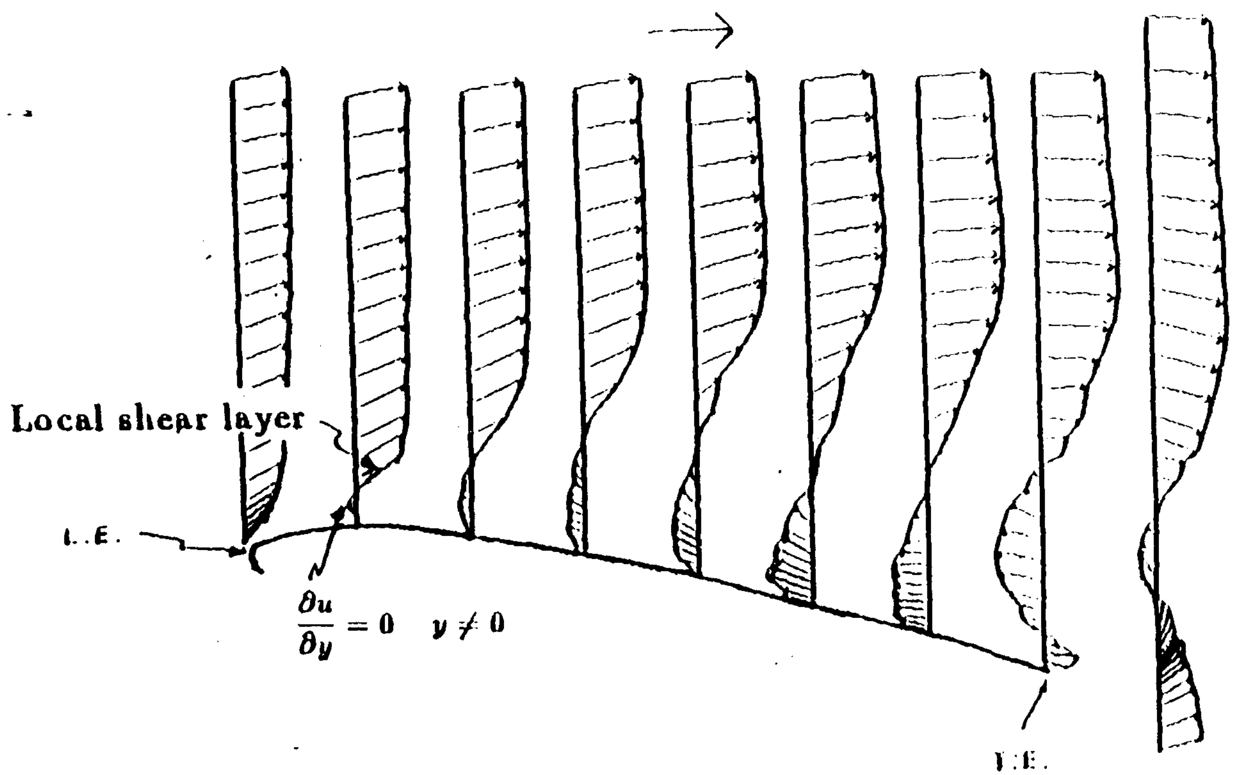

Figure 1a: Upstream moving separation (Shih, 1988).

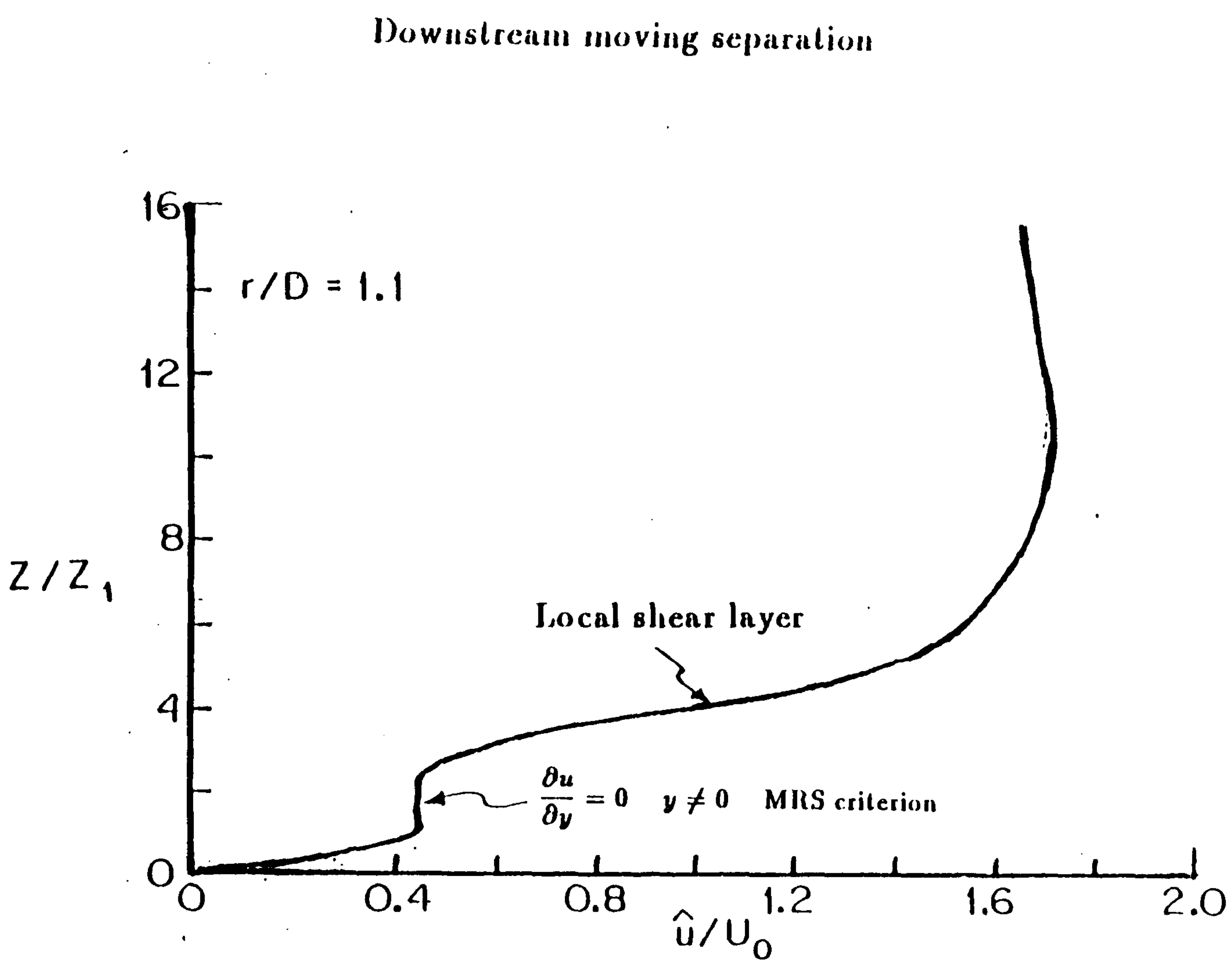

Figure 1b: Downstream moving separation (Didden and Ho, 1985).

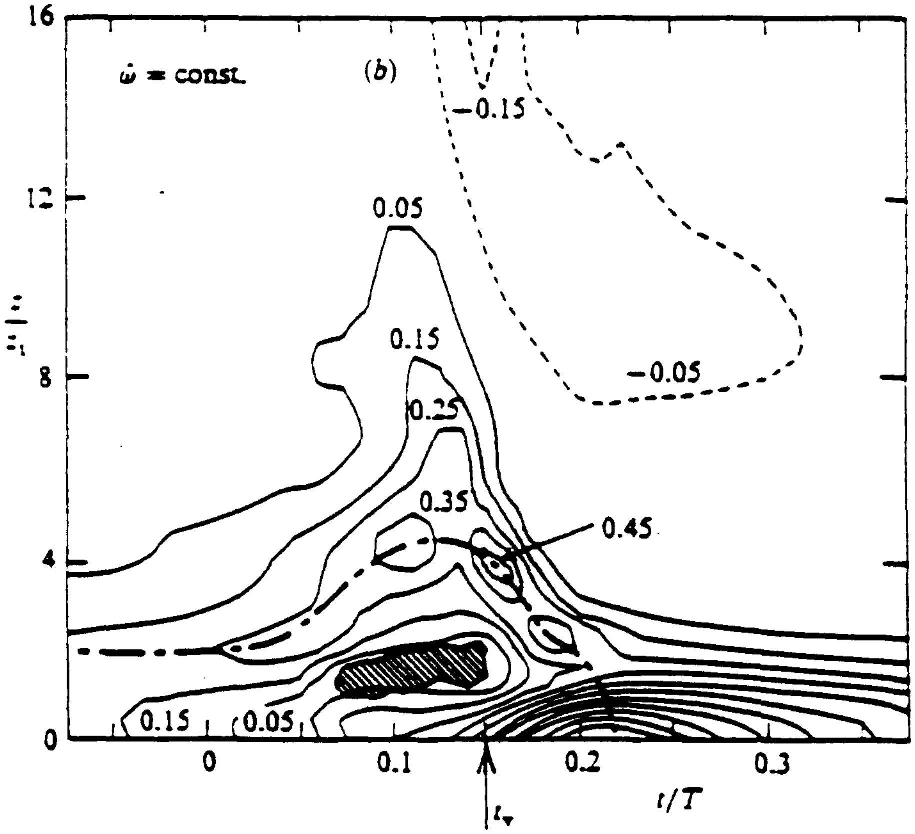

Figure 2: Secondary vortex ejection in vortex induced separation (Didden and Ho. 1985).

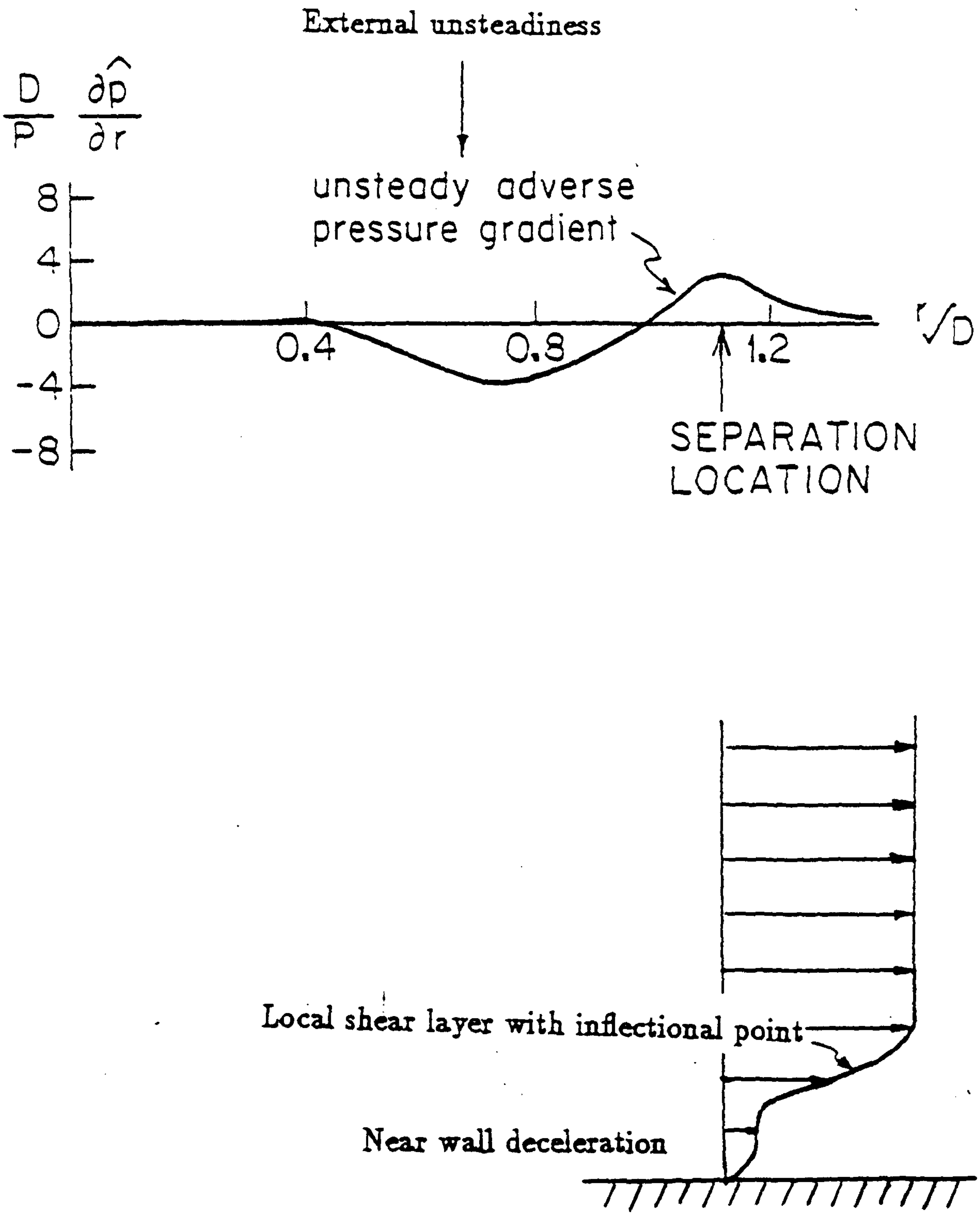

Figure 3: Unsteady separation mechanism.

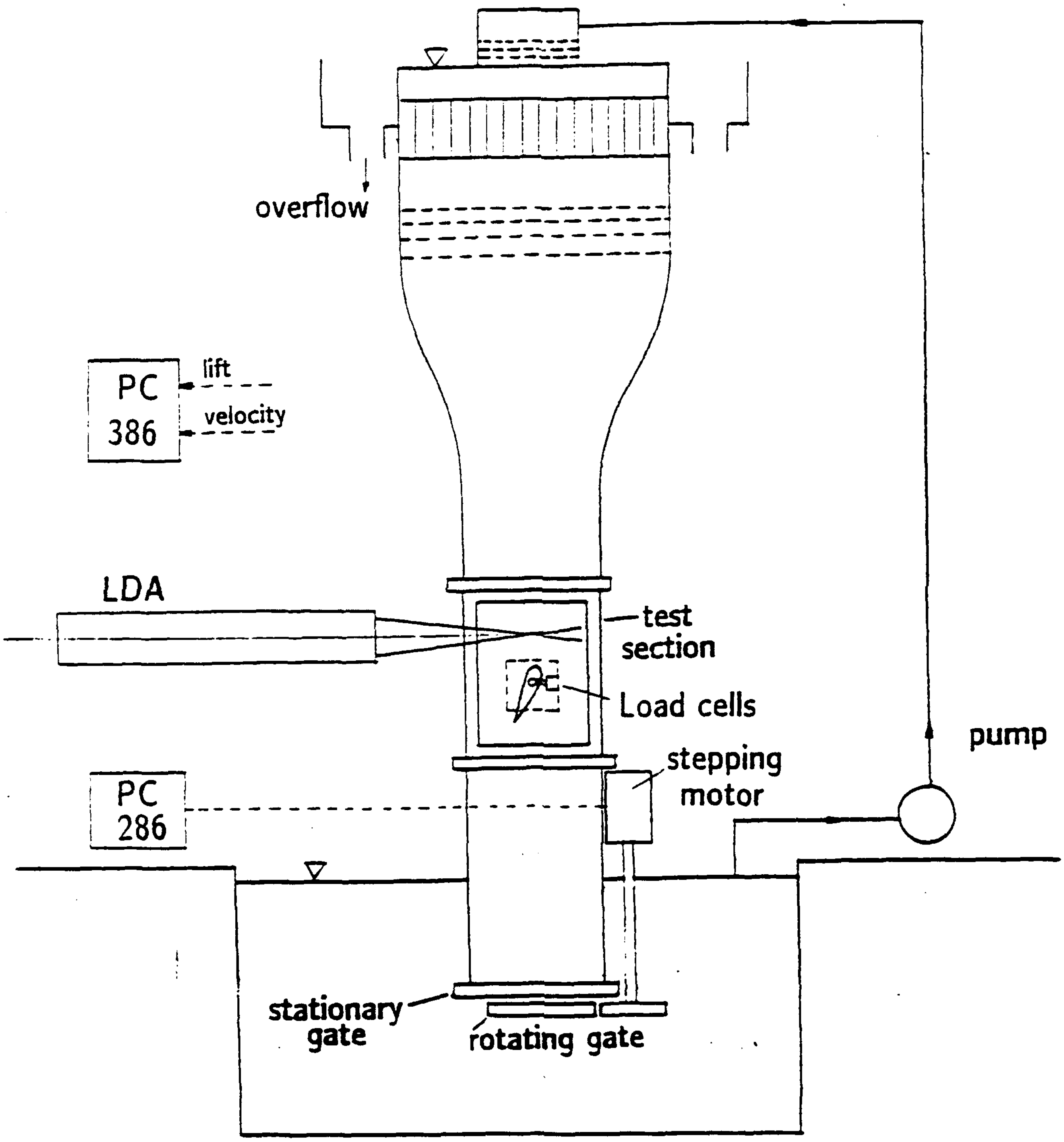

Figure 4: Unsteady water channel.

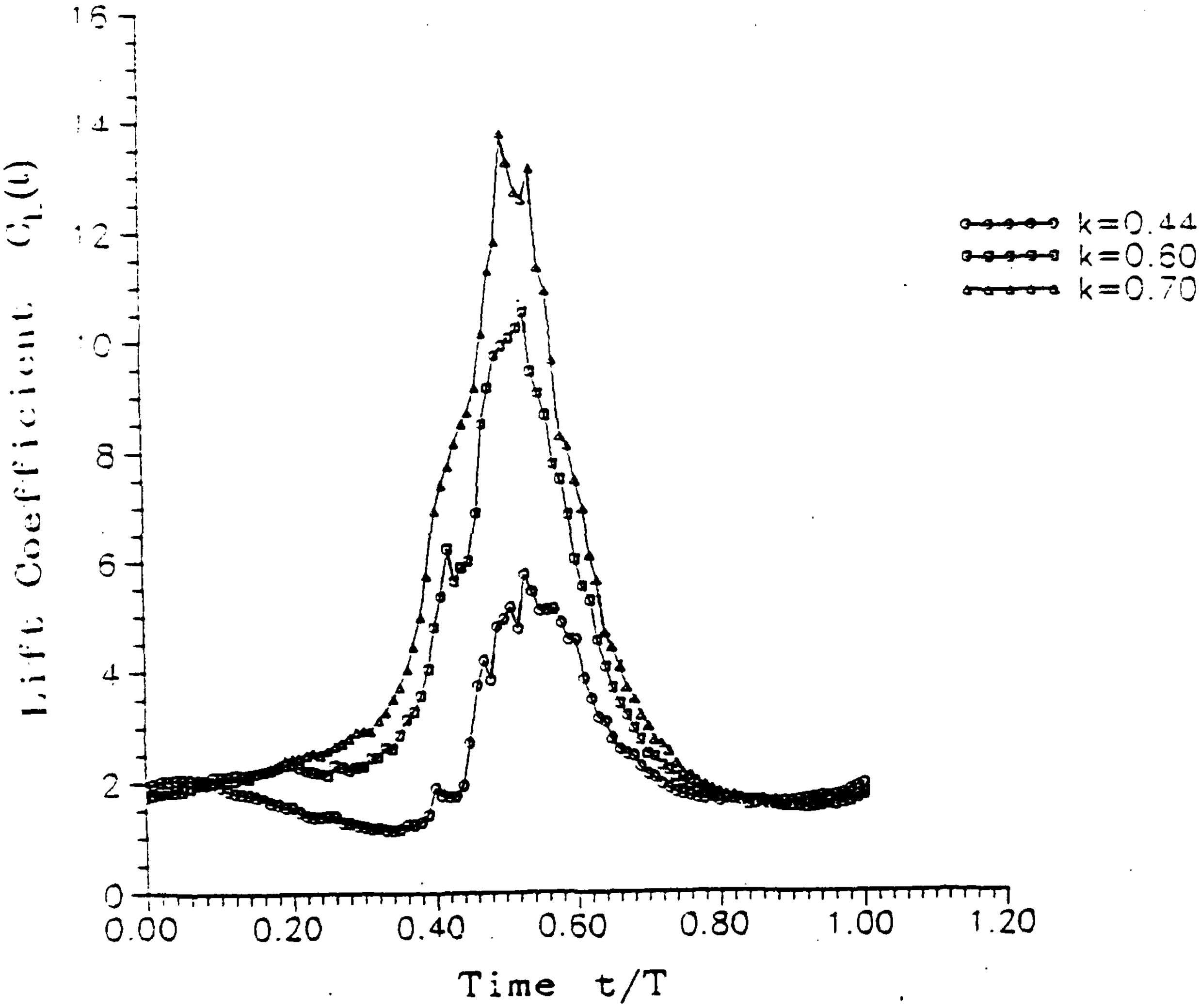

Figure 5: Variation of phase-averaged lift coefficient over a cycle for NACA 0012 at α=20°.

To appear in Applied Mech. Rev.

LIFT FORCE OF DELTA WINGS[1]

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ABSTRACT

On a delta wing, the separation vorticies can be stationary due to the balance of the vorticity surface flux and the axial convection along the swept leading edge. These stationary vortices keep the wing from losing lift. A highly swept delta wing reaches the maximum lift at an angle of attack of about 40° which is more than twice as high as that of a two-dimensional airfoil. In this paper, the experimental results of lift forces for delta wings are reviewed from the perspective of fundamental vorticity balance. The effects of different operational and geometrical parameters on the performance of delta wings are surveyed.

I: INTRODUCTION

An aircraft undergoing maneuvering requires a well-defined lift force in a wide range of angle of attack. For example, a 70° swept delta wing can continue to increase its lift until the angle of attack reaches approximately 40°. In contrast, a two dimensional steady NACA 0012 airfoil will reach its maximum lift at only about 15° angle of attack. At higher angles, the flow on the suction side of the airfoil does not follow the surface. Vorticity starts to accumulate and forms vortices. On a two-dimensional wing, there is no way of convecting vorticity downstream other than shedding downstream with the free stream velocity. The shedding of vortices is intermittent and, most importantly, is not in phase with the spanwise direction. Therefore, it results in a fluctuating and low lifting force; thus the 2D airfoil stalls. On the other hand, a delta wing separates at a fairly small angle of attack, say about 5° or less. The vorticity generated at the leading edge can be carried downstream by the velocity component along the inclined leading edges. When the vorticity diffused from the surface balances with the convected vorticity, the separation vortices become stationary. The stationary vortices make the potential flow near the leading edge create a convex curvature that

[1]Transmitted by AMR Associate Editor Dr. Mohamed Gad-el-Hak

produces a suction. The suction contributes to increased C_L even after the flow has *separated* at the leading edge. As the angle of attack increases, the vortex breaks down with the vortex burst propagating from the trailing edge to the apex. With further increasing angle of attack, the velocity above the suction side decreases. The ability of convecting vorticity is reduced and changes the balance of vorticity. Eventually the leading edge vortices cannot be held in place and thus start to shed. The three-dimensional equivalent to the two-dimensional stall occurs and the flow over the suction side separates globally.

It is clear that the main aerodynamic difference between the delta wing and the two-dimensional wing depends on the behavior of the separation vortices. The principal source of vorticity is at the leading edge. The vorticity diffuses from the surface into the flow and lumps into vortices. The vorticity balance between diffusion and convection at different operating conditions will then determine the state of the vortices, e.g. stationary, vortex burst as well as shedding. Therefore, we can understand the aerodynamics of a wing if the fundamental vorticity balance is clarified. This is the approach chosen for the review of the existing experimental works on the delta wing.

In the present paper, a brief summary of the fundamental concepts is first presented. Next, the different parameters affecting steady and unsteady flow over delta wings will be discussed. Finally, the results of the different schemes employed to control the lift will be examined.

II: VORTICES AND LIFT FORCE

2.1 General Features of Leading Edge Vortices

The two spiralling vortices on a delta wing are formed from the separated shear layers which originate from the leading edge (Fig. 1). On a wing with rounded leading edge, Earnshaw and Lawford (1964) found that these vortices did not appear until the angle of attack was more than 5°. For a sharp leading wing, the separation vortices start at a smaller angle of attack (Ericsson and Reding 1977). The transverse size of the L. E. vortices is in the order of the half span. A large

portion of the lift on the wing is contributed by these spiralling vortices, which produce suction footprints on top of the wing. The pressure measurements by Fink and Taylor (1967) in Fig. 2 show that the locations of maximum suction are beneath the cores of the vortices.

Secondary structures of the leading edge vortices have been observed. Small vortices which develop from the Kelvin-Hemholtz instability waves of the thin separating shear layer are superimposed on the large vortices (Gad-el-Hak and Blackwelder 1987). These small vortices (Fig. 3, Payne et al. 1988) are scaled with the thickness of the shear layer which is usually more than one order of magnitude smaller than the span. Under the L. E. vortices and slightly outboard from the cores, there is a pair of secondary vortices (Figs. 1-a, 2-a), induced by the primary vortices.

At large angles of attack, the L.E. vortices will suddenly expand in size. This is coupled with a sharp increase in the dynamic pressure and a decrease in axial velocity. This phenomenon is called vortex burst or breakdown. Flow visualizations obtained by Lambourne and Bryer (1961, Fig. 4) show that the transformation can take a very abrupt form. The measurements made by Hummel (1965) in Fig. 5 reveal that the vortex is spread out over a larger region after the breakdown as indicated in the flow visualization. The vortex breakdown is associated with changes in the lift characteristics of some but not in all types of delta wings (Section 3.1).

2.2 Balance of Vorticity

The solid surface is the only source of vorticity which enters the flow by being diffused into the boundary layer. In an attached flow, the vorticity is removed continuously by free stream convection. The vortical boundary layer stays thin and follows the surface. At the onset of separation, a local shear layer forms near the wall (Didden and Ho 1986). The shear layer is unstable and extracts energy from the high speed free stream onto the wall region. The high level vorticity in the shear layer lumps into large vortical structures. The boundary layer is substantially thickened and the vortices are convected downstream with the velocity of the free stream. A fully separated flow takes place. Therefore, the balance between surface vorticity flux and vorticity transport in the

free stream dictates the vorticity accumulation or depletion above solid surfaces. The importance of the vorticity balance concept was emphasized by Reynolds and Carr (1985) in their review of separation driven flows. The underlying assumption is that two and three dimensional separated flows are dominated by large concentrated vortices.

Reynolds and Carr (1985) have shown further that the surface vorticity flux is governed by the local pressure gradient, transpiration through the surface, and motion of the surface itself. On a delta wing, the amount of vorticity roll-up into the vortex depends on the condition of the boundary layer at the leading edge prior to separation because the local curvature determines the pressure gradient.

Next, let us look at the effects of vorticity convection. On a two dimensional airfoil, separation from the leading edge does not lead to a stationary vortex. The free stream velocity is normal to the leading edge and there is no intrinsic convection to remove vorticity. All the vorticity is simply convected with the vortex by the free stream as a whole. Shih (1988) has shown that the time spent by the vortex on the chord is an intrinsic time scale in determining the aerodynamic properties of a wing. Rossow (1978) tried to stabilize the vortex on a two dimensional wing by providing artificial suction from the side and using a vertical fence to shield the vortex from the free stream. He found that the vortex was too sensitive to stay stationary, and an inclination of 10° to 20° from the leading edge was observed. This shows that axial convection along the core is essential in maintaining a stationary vortex. On the delta wing, a stationary leading edge vortex is possible due to the slanted leading edge. The swirl in the core depends on the amount of bounded vorticity fed through the shear layer and the magnitude of axial convection along the vortex core. The convected vorticity is determined by the component of the free stream velocity in the direction parallel to the leading edge. This component of the free stream velocity is a function of the angle of attack, α, angle of sideslip, β, and sweepback angle, Λ_{LE}, as shown in Fig. 6. The swirl produces suction on the surface. Therefore, lift is a function of these parameters. Based on the above reasoning, the swirl angle, ψ, between the perpendicular and axial velocity components along the leading edge would reflect the vorticity balance necessary for a stationary vortex. Lambourne and Bryer (1961) suggested that ψ is important in determining the location of vortex breakdown over a delta wing. The evidence

supporting this view will be provided in Section III. A more detailed review of the theories relating to swirl angle at the edge of the viscous core and breakdown has been given by Leibovich (1984).

2.3 Lift Prediction

The purpose of this paper is mainly to survey the experimental studies on the lift of delta wings. Review of theoretical or numerical prediction methods is not within the scope of the present paper. A review of various lift prediction methods was provided by Parker (1976) as well as Ericsson and Reding (1987). However, a simple and effective theory developed by Polhamus (1971) will be referred to in order to understand the effects of several parameters on the lift forces generated by vortices and the potential effect.

Based upon the leading edge suction analogy, Polhamus predicted the total lift on a delta wing by separating the normal force into potential and vortex components. The potential lift term is based on the lifting-surface theory, taking into account the Kutta condition at the trailing edge. The vortex lift term is modeled by the suction force generated by the equivalent attached flow around the edge. The only condition necessary for the analogy to hold is that the separation must reattach on the upper surface. No detailed knowledge of the shape, strength and position of the vortex is required. It is interesting to note that the vortex lift term is sensitive only to angles of attack. The sweepback angle dependence comes solely from the potential lift term (Fig. 7). According to this theory, the airfoil depends more and more on the vortex for lift as the sweepback angle increases and it can offer reasonable predictions on the lift of delta wings until vortex breakdown occurs over the wing surface. The Kutta condition most likely will not be held when high levels of fluctuation become dominant in flows with vortex bursting. The assumption in the theory breaks down and the predictions are of course invalid. Campbell (1976) compiled the lift coefficients for wings with different swept back angles (Fig. 8) and showed that vortex breakdown limited the application of Polhamus' prediction.

III: LIFT OF STEADY DELTA WINGS

Parameters which affect steady flow over a delta wing include angle of attack, sweepback angle, angle of sideslip, leading edge profile, trailing edge geometry, Reynolds number, Mach number, and free stream turbulence. In the following sections, we will examine the measured lift as a function of these parameters.

3.1 Effects of Angles of Attack, Sweepback, and Sideslip

The effects of sweepback angle, Λ_{LE}, on lift are shown in Fig. 9 as a function of the angle of attack, α (Earnshaw and Lawford 1964). The wings used are slightly cambered and therefore the C_L does not pass zero at $\alpha = 0°$. C_L increases with the angle of attack until reaching a maximum value. The delta wings with $\Lambda_{LE} = 65°$ and 70° produced the best performance in terms of maximum lift coefficient. For airfoils with smaller sweepback angles, the maximum lift coefficients decreased significantly. A comparison between the measurements and the predictions by the leading edge suction analogy is shown in Fig. 10. The breakdowns of the vortices at the trailing edge and the apex are also indicated in the figure. For wings with large sweepback angles, $\Lambda_{LE} = 70°$ or 75°, the measured C_L curves show that the theoretical lift coefficients have been achieved. The angle of attack at the maximum C_L corresponds to that of vortex breakdown occurring at the trailing edge. For wings with smaller sweepback angle, measured C_L is always lower than that of the predicated value. No obvious correlation between the vortex breakdown and the change of the lift coefficient curve can be observed (Fig. 10-a). This is different from wings with larger sweepback angle (Fig. 10-b), because a major portion of the lift of the wing with the large sweepback angle is contributed by the vortex (Fig. 7) and hence the vortex breakdown has a strong effect on the lift. For $\Lambda_{LE} > 75°$, the projection of a wing at a high angle of attack in the direction perpendicular to the flow is close to a three-dimensional slender body. The sinus mode instability dominates in the wake and vortex asymmetry occurs before breakdown. The full vortex lift cannot be achieved.

The effects of yaw angle, β, on the position of vortex breakdown is shown in Fig. 11 from the data of McKernan and Nelson (1983). The vortex would burst closer to the apex on the windward side and farther away on the leeward side. The pressure measurements of Hummel (1965) in Fig. 12

show the corresponding shift. However, the normal force measured by Harvey (1958) in Fig. 13 shows only a weak dependence on yaw. Ericsson and Reding (1977) suggested that the effect of β can be included in an effective Λ_{LE} for a small angle of attack. Hence, the normal force does not change much with β.

The variation of the vortex bursting position described above can be traced to an effective change in the balance between vorticity surface flux and convection. The vorticity is generated along the leading edge and convected away from the leading edge. The velocity component in the streamwise direction and the sweepback angle of the leading edge determine the swirl angle, β, which indicates the direction of the vorticity transport. An increase in the angle of attack, a decrease in the sweepback angle or an increase in the yaw would increase the ratio between circumferential to axial flow (Fig. 6). Sforza et al. (1978) measured the flow over a $\Lambda = 75°$ delta wing and showed that the circumferential velocity at the core increases with the angle of attack. The swirl angle will increase accordingly. Fig. 14 shows a summary of leeside vortex breakdown locations versus swirl angle, ψ, for different angles of attack, sweepback and yaw angles. The collapse of the breakdown positions in the swirl angle suggests that all three parameters affect the stability of the vortex through the same mechanism, i.e. the vorticity balance. For large sweepback angles, $\Lambda_{LE} = 75°$, 80° and 85°, the collapse is not very good because the interaction of two vortices become important at these angles.

Payne (1987) surveyed the measurements made of the swirl angle at the edge of the viscous core upstream of vortex breakdown in vortex tube experiments. He reported that the angle varied from 38° to 55° for a spiral breakdown. Payne's own measurements over a delta wing ($\Lambda_{LE} = 85°$) was 44° at $\alpha = 40°$ while Hummel (1965) measured 53° ($\Lambda = 79°$) at $\alpha = 31°$. These values are in the same range of the present data (Fig.14) which varies from 32° to 66° even though the angles in Fig. 14 are deduced based on geometry at the leading edge.

3.2 Effects of Leading Edge Profile

Bartlett and Vidal (1955) studied the effects of leading-edge sharpness on three wings with different

symmetric cross sections and thickness-to-cord ratios. They found that the wing with beveled edges produced the maximum slope for C_L vs α (Fig. 15), because the flow separated right at the sharp edge and produced a high suction. On the wings with elliptic or round edges, separation occurred downstream from the leading edge. The position of separation depended on the Reynolds number and the local curvature which determined the pressure gradient. Vortex formation was delayed and the lift was lower. The effect of local curvature was investigated by Wentz (1972). He examined a wing with spanwise camber and measured a slightly lower lift coefficient than that of conical and apex cambered wings up to $\alpha = 35°$. However, maximum lift was somewhat increased. Based on the pressure measurements, the camber near the apex significantly modifies the pressure distributions, but not elsewhere along the leading edge. The smaller adverse pressure gradient at the apex of the spanwise camber wing postponed the separation further inboard onto the convex surface. This delayed the roll-up of the vortex and resulted in less lift. Other experiments by Lamar (1977) with a linearly twisted bat wing (Fig. 16) showed that a gain in lift was achieved when a convex surface was placed on the suction side of the airfoil. This gain in lift is due to a longitudinal camber effect as indicated by the non-zero lift generated at a zero angle of attack. When the wing was inverted, the lift decreased. Earlier, Lambourne and Bryer (1961) demonstrated through flow visualizations that longitudinal camber with a convex upper surface can delay vortex breakdown.

3.3 Effects of Trailing Edge Geometry

Wentz and Kohlman (1971) measured the lift coefficients of delta wings with modified trailing edge. The trailing edge of one of the wings was extended to become diamond-shaped. The trailing edge portion of the other wing was cut to form an arrow-shaped wing. The lift coefficient of the arrow wing is higher than the diamond wing over the whole range of the angles of attack. Through the trailing edge boundary condition and aspect ratio effects for both vortex and potential lift terms, Polhamus (1971) predicted higher lift coefficients for an arrow wing compared with a diamond wing. The theory overpredicts the arrow wing and underpredicts the diamond wing. The difference can be corrected by using the argument of equivalent delta wings (Ericsson and Reding 1977).

Wentz and Kohlman also found that the trailing edge apparently has no effect on the vortex breakdown location. This is reasonable since the trailing edge does not affect the vorticity balance which is dictated by the swirl angle between the perpendicular and parallel velocity along the vortex. However, trailing edge flap deflected upward and downward can advance or retard vortex breakdown. The presence of the flap changes the circulation and modifies the pressure gradient over the whole wing. The axial vorticity convection which influences the vortex breakdown is then modified.

3.4 Reynolds Number

Elle (1961) studied the location of a vortex over sharp edged delta wings in both water and air and concluded that the flow is insensitive to Reynolds number. Fig. 18 shows a compilation of data by Erickson (1982) taken from water and wind tunnels and in flight. The Reynolds numbers range from 9.8×10^3 to 4.0×10^7. These results confirmed previous experiments which showed that vortex location and breakdown are governed by an inviscid mechanism. The lift data (Fig. 19) taken by Lee, Shih and Ho (1987) further showed that Reynolds number insensitivity extends to aerodynamic forces acting on delta wings. They also show that the vortex breakdown location is not a function of the Reynolds number for sharp edged wings. However, Erickson (1982) suggested that the flow is insensitive to Reynolds number for sharp edged wings only because the separation is fixed along the edge. He reasoned that boundary layer laminar/turbulent transition on wings with round leading edges and flaps would still be sensitive to the Reynolds number. Erickson's arguments were substantiated by Lee (1955) who showed variations in the secondary separation line on the surface through oil-film visualizations from $Re = 5 \times 10^5$ to 2×10^6. The separation location is known to be dependent on the turbulent/laminar state of the boundary layer. Hence the vortex formation and the local pressure distributions will be functions of the Reynolds number. The effects discussed in the section of leading edge profile (Section 3.2) must be a combination of local curvature and viscous effect. In addition, the strength and location of the secondary separation on the surface induced by the primary vortex would also be affected since this phenomenon is also viscous in nature.

The size of the L. E. vortex is independent of the Reynolds number. As the free stream velocity increases, the viscous core decreases in size due to a thinning of the boundary layer at the leading edge. This effect by itself, apparently, is not strong enough to affect the vorticity balance which is governed by the swirl angle and pressure gradient. A more in-depth discussion of Reynolds number sensitivity over delta wings is given by Payne (1987). In vortex tube experiments (Escudier and Zehnder 1982), the Reynolds number was a dominating parameter. It should be noted that there are fundamental differences between vortices generated in a tube and over a delta wing. As pointed out by Leibovich (1984) vorticity is shed into the center of the tube by a vane type generator producing a spiral vortex with constant vorticity. On a delta wing, vorticity is constantly fed into the core from the leading edge resulting in an almost linear increase of vorticity along the vortex. Wedmeyer (1982) found that velocity profiles measured in vane type generators did not compare well with those measured over delta wings.

3.5 Mach Number Effects

In the supersonic regime, the separated leading edge vortex is replaced by a series of attached shock waves and Prandtl-Meyer type expansions depending on Mach number, angle of attack and wing geometry. Stanbrook and Squire (1964) showed that the important parameters in supersonic flow are the angle of attack and Mach number perpendicular to the leading edge. They found that the flow can take on three different forms as illustrated by Squire (1976) in Fig. 20. Later on, Wood and Miller (1985) further classified the flow into six regimes depending on the existence and nature of shock induced separation on the top surface. It is interesting to note that the leading edge separation reappears at large enough angles of attack regardless of Mach number. Rizzetta and Shang (1986) used a Navier-Stokes code to simulate supersonic flows over a delta wing. The predicted pressure distribution matched experimental data very well. Leading edge vortices can be observed from the numerical results.

A drop of lift coefficient with increasing Mach number will happen (Polhamus 1971) because the separation line on the pressure surface would gradually move outboard toward the leading edge

resulting in a weaker vortex. The vortex totally vanished when the stagnation line reached the leading edge where no flow reversal occurred. This corresponds to the situation when the Mach cone coincides with the leading edge at the Stanbrook-Squire boundary between regions A and B in Fig. 20. Therefore, this effect would be more severe for delta wings with smaller sweepback angles. In addition, Squire, Jones and Stanbrook (1961) pointed out that the lift would be further lowered at large angles of attack and high Mach numbers when the low pressure region in the vortex core reaches the vacuum limit.

3.6 Effects of Free Stream Disturbances

Very little work is reported in the literature concerning free stream effects on the vortex. Lambourne and Bryer (1961) found no effect on the vortex when a spoiler was placed either at or in front of the apex. However, Lee, Shih and Ho (1987) found that the breakdown location became very unstable when the free stream turbulence was increased from 0.5% to 1.5%. The result suggests that the breakdown location is sensitive to the transverse velocity disturbances but not to the streamwise velocity perturbations. It appears that more work is required in this area.

IV. FLOW OVER UNSTEADY WINGS

4.1 Time Scales

When a delta wing is placed in an unsteady environment, many types of time scales exist; the period of the unsteady motion, the response time for the stationary leading edge vortices to perturbations and the convection time of the shedding leading edge vortices. The first one is an externally imposed time scale. The latter two are intrinsic to the flow field.

The response time of the unsteady wing depends on the mechanism governing the stability of the leading edge vortex. The vorticity balance concept determines two time scales. First, changes in the vorticity generation along the leading edge are transmitted to the core in one local turn-over time.

This time is maximum at the trailing edge and decreases towards the apex due to the difference in transverse lengths. Therefore, the vortex around the apex is more sensitive to disturbance than any other place along the leading edge. Second, upstream disturbances are convected throughout the vortex core in a time, C/U, which scales with the streamwise velocity along the vortex. Since the latter time is always longer, streamwise convection becomes the limiting factor for the vortex to respond to any imposed disturbance. In the following sections, we will look at how these time scales play their roles in different types of unsteady motion.

The external perturbation produces a time-varying pressure gradient. The surface vorticity flux will change accordingly. In the case of a wing with small sweepback angle, the leading edge vortices may not be able to hold to their positions due to excess vorticity diffusion and low level vorticity convection. The vortices will convect from the apex to the trailing edge. After the vortices leave the trailing edge, the lift drops. The time of the convecting vortices spent on the delta wing becomes another intrinsic time scale. This is similar to the flow over a 2D wing.

Obviously, the aerodynamic properties of the wing are dictated by the relative importance and the ratio of these time scales. We will discuss this aspect in the following sections.

4.2 Types of Unsteady Flows

Experimental investigation of unsteady delta wing aerodynamics has been limited due to the difficulty in producing well controlled time-varying free streams in the laboratory. The unsteady free stream needs to be produced by accelerating or decelerating the whole fluid mass in the test section. The interaction between the control device and non-linear characteristics of the pump or the blower is non-trivial. In a vertical water channel, Shih, Lee and Ho (1987) were able to achieve various velocity waveforms by operating it in a constant head mode. In this case, the non-linear feature of the pump is isolated. The velocity in the test section is a function of the flow resistance governed by the opening area of the gate at the exit of the test section. By properly controlling the opening area, the test speed can be varied as a function of time.

Most other experiments subject the wing to some form of periodic motion in a steady free stream. Pitching involves varying the angle of attack by pivoting the wing about a certain chordwise location. This motion produces a continuous change not only in the angle of attack, but also in the effective free-stream velocity approaching the wing. Other modes are the plunging and heaving motion, where the airfoil is in up-down or forward-back movements. Both modes can produce stepwise or continuous change of the effective angle of attack. Wing rock, another unsteady phenomenon which involves back and forth rolling about the centerline axis, has been observed in real flight. This and other unsteady effects can drastically influence the performance of delta wings. For a review on unsteady separated lifting surfaces, the paper by Ericsson and Reding (1987) provides a detailed reference.

4.3 Pitching, Plunging and Heaving

In a flow visualization experiment with a pitching delta wing (Gad-el-Hak and Ho 1985, Gad-el-Hak 1987), the two leading edge vortices first rolled up at the trailing edge tip and then migrated toward the apex. A well organized wake behind the wing was formed when the reduced oscillating period, UT/C, equalled 1 where T is the period of external unsteady motion. In a series of plunging experiments, Lambourne, Bryer and Maybrey (1969) also found that the vortex required a time period UT/C = 1 to reach its new equilibrium position. Similar results by Maltby et al. (1963) were reported for a heaving delta wing. These experiments suggest that the slow convection along the vortex limits the response time of the flow such that all periodic disturbances should scale with the characteristic time of C/U as discussed above. In a related experiment, Patel (1980) subjected the delta wing to vertical gusts generated by a movable section of his wind tunnel. Fig. 21 shows the measured lift amplitude and phase as a function of the oscillating periods. The tested range of T is about one order of magnitude longer than the convection limit, C/U. The measured data are not very sensitive to the oscillating frequency. It suggests that the vortex delay effect was not important in this frequency range and that the potential flow dominated. The constant phase lag which appeared in the data was probably due to the difference between the convection speed of the vertical

disturbance and the freestream velocity as mentioned by the author.

4.4 Unsteady Freestream

Freymuth (1987) used titanium tetrachloride to visualize the response of a delta wing in a flow starting from zero speed. The sequence of pictures showed the formation of leading edge vortices of a delta wing at constant angle of attack in an accelerating flow. The vortex breakdown location was observed to move upstream when the flow in the wind tunnel was accelerating and vice versa during deceleration (Lambourne and Bryer 1961). When the freestream returned to a steady speed, the bursting point returned to its average position. This result was confirmed by Lee, Shih and Ho (1987). To explain these observations, we recall that a favorable pressure gradient increases surface flux of vorticity in the boundary layer at the leading edge resulting in an increase in peak vorticity in the core. This increase in surface flux of vorticity produces a larger swirl angle. Furthermore, Lambourne and Bryer (1961) showed in their analysis that any pressure gradient in the freestream is magnified in the vortex core. A large swirl angle causes the breakdown to migrate upstream (Fig. 14). During deceleration, the adverse pressure gradient disturbs the vortex by locally reducing the convection of vorticity along the core, thereby disrupting the vorticity balance and affecting the vortex burst.

When Lee, Shih and Ho (1987) imposed a free-stream velocity oscillation in the water tunnel, the vortex breakdown occurred at the mid-chord region and no significant change in the vortex breakdown location was observed. Gursul and Ho (1989) studied this problem for wings with different aspect ratios and in a wide range of angles of attack. They found that the vortex breakdown position could be very sensitive to the free stream variation, if the averaged breakdown location was near the trailing edge. The lift of the delta wing was also measured by them. For the cases of small angle of attack, the phase averaged C_L is not a function of the reduced frequency and can be scaled by the period of the freestream variation (Fig. 22). These results again indicated that unsteady vortex effects have not come into play since the vortices have ample time to respond to the imposed disturbances. At a large angle of attack, the leading edge vortices do not stay stationary.

The time of vortices convecting from the apex to the trailing edge becomes an important scale in dictating the change of C_L. The period of the free stream variation is not the only governing time scale and the C_L curves do not collapse as those in Fig. 22.

4.5 Wing Rock

The phenomenon of wing rock has been observed during flights of the aircraft with a delta wing platform marked by a sustained large amplitude oscillatory motion (Hwang and Pi 1979). A time history of the normal force and roll angle of an 80° delta wing tested in the wind tunnel is shown in Fig. 23 by Levin and Katz (1984). The average normal force experiences a sudden drop when the rock starts. Whether a delta wing will exhibit wing rock behavior or not depends on the initial roll and angle of attack (Fig. 24). The roll amplitude and oscillation frequency were observed to depend on the angle of attack and freestream velocity (Levin and Katz 1984). Ericsson (1984), suggested that asymmetric vortex shedding rather than vortex breakdown is the key mechanism leading to wing rock. He argued that vortex breakdown cannot produce wing rock because Levin and Katz (1984) observed wing roll before vortex breakdown and that the phenomenon is known to occur only on very slender wings. In addition, a loss of lift over the side of the wing with vortex breakdown produces a roll which increases the effective angle of attack. Consequently, the breakdown location is advanced farther upstream resulting in no restoring moment. In the case of asymmetric vortex shedding, a limit cycle mechanism is produced when the wing rolls to one side resulting in an increase in the effective apex angle based on the regime chart in Fig. 25. This motion momentarily reduces the tendency for the vortex to shed asymmetrically. The leading edge vortex re-forms on the wing at a later time due to the vortex time lag effect discussed earlier and then produces the necessary restoring rolling moment.

Another way of looking at the vortex shedding mechanism based on vorticity balance is as follows. When the side of the wing tilts downward due to roll, the vorticity generation is increased due to an increase in the local pressure gradient at the leading edge as the stagnation point shifts in the opposite direction. This leads to the formation of a stronger vortex which can resist convection

downstream. The formation time is again determined by C/U which sets a limit of oscillation frequency of C/UT = 1. On the other side of the airfoil, the vortex is washed downstream due to an increase in the convection as the leading edge vortex is exposed more to the freestream. This cycle is repeated when the wing rolls again in the opposite direction.

V. CONTROL OF LIFT

Most of the different schemes used to control the flow over delta wings reported here attempt to modify the leading edge vortex. The methods can be classified under blowing, suction and mechanical flaps applied at strategic locations on the suction surface either in a steady or in an unsteady fashion. A discussion on potential applications of vortex flaps is given by Lamar and Campbell (1984). Another scheme which does not fall in the categories mentioned above is the effect of density and viscosity variations through heating. These methods discussed here are effective in many aspects, but also have drawbacks. It is clear that the future trend of research will be the development of efficient control techniques through fundamental understanding of the physical mechanisms governing the aerodynamics.

5.1 Blowing

Various attempts have been made to alter the separation vortex by blowing along the leading edge in different directions. Trebble (1966) was able to enhance the lift by blowing outward away from the wing along the edge. The effect of blowing produced a stronger vortex located further outboard. An increase in drag was also measured due to the reverse thrust generated by a part of the high momentum fluid directed upstream. Bradley and Wray (1974) and Campbell (1976) achieved higher lift, a delay in stall and better drag polar as a result of the spanwise blowing along the leading edge. The spanwise blowing could be due to an increase of the effective wing area instead of the modification of the vortices. Flow visualization pictures taken by Bradley and Wray (1974) of the vortex exhibited a more coherent core and delay in breakdown which is due to the increase in axial convection. When compared with Polhamus' theory, full vortex lift was achieved beyond the normal

angle of attack for maximum lift (Fig. 26). Favorable results were also achieved by Wood and Roberts (1987) who directed the fluid tangentially upward past the round leading edge of a half delta wing. The pressure measurements shown in Fig. 27 suggest that leading edge separation was delayed for a small angle of attack and that the vortex was strengthened and localized at large angles. The reason for this is the increase in vorticity generation prior to separation due to changes in the local pressure gradient. Another method was attempted by Gad-el-Hak and Blackwelder (1987) who applied periodic blowing and suction at the leading edge. Although flow visualizations showed that the secondary vortices on the shear layer were more organized, no pressure data was available to deduce the effects on the aerodynamic forces acting on the wing.

5.2 Suction

Hummel (1967) investigated the effect of applying suction at the trailing edge and measured an increase of suction on the top surface while the bottom pressure profiles were not altered. A general increase in lift at a high angle of attack was observed with no gain at small to moderate angles of attack (Fig. 28). This is reasonable since suction only affects the vortex which contributes only a small portion of the lift at small angles of attack. At larger angles, suction at the trailing edge reduces the local adverse pressure gradient and increases axial convection along the vortex. As a result, a delay in vortex breakdown can be expected resulting in higher lift.

5.3 Flaps

Both stationary and moving flaps of different shape and size have been placed at or near the leading edge in an attempt to modify the evolution of the separation vortex. An experiment with stationary flaps was performed by Wahls, Vess and Moskovitz (1986) who placed triangular shaped vertical fences at various locations close to the apex. Their flow visualizations showed the generation of streamwise vortices from the top of the fence. The new vortex eventually intertwined around the original vortex which was sheo from the leading edge resulting in premature bursting. Rao and Buter (1983) also generated two pairs of streamwise vortices when they created an apex-flap through

upward deflection of the apex at 25% chord. Lift was increased for small angles of attack due to the new leading edge vortices which were generated on the apex and normally would not exist at this angle. At moderate to high angles of attack, lift was lower than the basic wing. Although no visualizations were provided, this loss of lift was probably due to premature bursting of the main vortex as a result of the interaction with the apex vortex, as has been observed by Wahls, Vess and Moskovitz (1986). In another attempt, Marchman (1981) investigated the effects of upward deflection of a leading edge flap. The measurements in Fig. 29 show an increase of lift at low angles of attack but a loss of maximum lift. This is due to an effective increase in the swirl angle as a result of the deflected flaps. In addition to the lowered peak lift, an increase in drag was measured for all angles of attack reported. This type of flow control is probably more useful in conjunction with additional leading edge devices which can reduce the drag penalty. Of the ones tested by Rao and Johnson (1981) for this purpose, the combination of vortex plates and vertical fences produced the most drag reduction by creating a separation zone at the leading edge.

A concept borrowed from insect flight was the flapping delta wing experiment of Spedding, Maxworthy and Rignot (1987). Two triangular shaped extensions hinged along the leading edge were allowed to flap continuously at a frequency much faster than the response time of the original vortex. The idea was to generate a much stronger unsteady vortex through the flapping motion to enhance lift. Fig. 30 shows the increase in circulation over non-flapping delta wings as a function of the flapping frequency. Note that the reduced frequency was based on average radian frequency measured at the mean flap width located at $x/c = 0.5$.

5.4 Heating

Marchman (1975) looked at the effects of heating on delta wing performance. The surface was heated close to twice the free-stream temperature. Their measurements showed that heating has virtually no effect on the lift and pitching moment suggesting that variations in density and viscosity do not play an important role in the generation of the leading edge vortex. However, an increase of up to 25% in drag was recorded at large angles of attack. This is probably due to a combination of

an earlier transition of the thermally stratified unstable boundary layer and the increase of viscosity.

VI. CONCLUDING REMARKS

A review of experimental data for delta wings under both steady and unsteady conditions was presented from a vortex dynamics point of view. Vorticity balance provides the framework for understanding the effects of different parameters on the wing lift; stationary leading edge vortices result from the balance between vorticity surface flux and freestream convection. The surface flux of vorticity depends on the condition of the boundary layer on the leading edge prior to separation, while vorticity convection depends on the component of the freestream along the vortex. These vortices on the suction surface provide an important contribution to the lift of a delta wing, especially for the wings with large sweepback angle. Methods of either altering the vorticity generation near the leading edge or changing the vorticity convection along the cores can be effective in controlling the lift.

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REFERENCES

Bartlett, G.E. and Vidal, R.J., "Experimental Investigation of Influence of Edge Shape on the Aerodynamic Characteristics of Low Aspect Ratio Wings at Low Speeds", J. Aero. Sci., Vol 22, 1955, pp. 517-533.

Bradley, R.G. and Wray, W.O., "A Conceptual Study of Leading-Edge-Vortex Enhancement by Blowing", J. Aircraft, Vol.11, No. 1, Jan. 1974, pp. 33-38.

Campbell, J.F., "Augmentation of Vortex Lift by Spanwise Blowing", J. Aircraft, Vol. 13, No. 9, Sept. 1976, pp. 727-732.

Didden, N. and Ho, C.M., "Unsteady Separation in a Boundary Layer Produced by an Impinging Jet", J. of Fluid Mech., Vol. 160, 1985,

Earnshaw, P.B. and Lawford, J.A., "Low-Speed Wind Tunnel Experiments on a Series of Sharp-Edged Delta Wings", Aero. Res. Council, R M No. 3424, 1964.

Elle, B.J., "An Investigation at Low Speed of the Flow near the Apex of Thin Delta Wings with Sharp Leading Edges", Aero. Res. Council, R M No. 3176, 1961.

Erickson, G.E., "Water-Tunnel Studies of Leading-Edge Vortices", J. Aircraft, Vol. 19, No. 6, June 1982, pp. 442-448.

Ericsson, L.E., "The Fluid Mechanics of Slender Wing Rock", J. Aircraft, Vol. 21, No. 5, May 1984, pp. 322-328.

Ericsson, L.E. and Reding, J.P., "Approximate Nonlinear Slender Wing Aerodynamics", J. Aircraft, Vol. 14, No. 12, Dec. 1977, pp. 1197-1204.

Ericsson, L.E. and Reding J.P., "Fluid Dynamics of Unsteady Separated Flow. Part II. Lifting Surfaces", Prog. Aero. Sci., Vol. 24, pp. 249-356, 1987.

Escudier, M.P. and Zehnder, N., "Vortex-Flow Regimes", J. Fluid Mech., Vol. 115, 1982, pp 105-121.

Fink, P.T. and Taylor, J., "Some Early Experiments on Vortex Separation", Aero. Res. Council, R M No. 3489, 1967.

Freymuth, P., "Further Visualization of Combined Wing Tip and Starting Vortex Systems", AIAA J., Vol.25, No. 9, Sept. 1987, pp. 1153-1159.

Gad-el-Hak, M., "Unsteady Separation on Lifting Surfaces", Appl. Mech. Rev., Vol. 40, 1987, pp. 441-453.

Gad-el-Hak, M. and Blackwelder, R.F., "Control of the Discrete Vortices from a Delta Wing", AIAA J., Vol 25, 1987, pp. 1042-1049.

Gad-el-Hak, M. and Ho., C.M., "The Pitching Delta Wing", AIAA J., Vol. 23, No. 11, Nov. 1985, pp 1660-1665.

Gursul, I. and Ho, C.M., "Experiments on Two- and Three-Dimensional Lifting Surfaces in an Unsteady Free Stream", Bulletin of Amer. Phy. Soc., Vol. 34, p. 2307, 1989.

Harvey, L.K., "Some Measurements on a Yawed Slender Delta Wing with Leading-Edge Separation", Aero. Res. Council, R M No. 3160, 1958.

Hummel, D., "Untersuchungen uber das Aufplatzen der Wirbel an schlanken Deltaflugeln", Z. Flugwiss., Vol. 13, No. 5, 1965, pp. 158-168.

Ho, C.M., Gursul, I., Shih, C. and Lin, H., "Unsteady Separation Process and Vorticity Balance on Unsteady Airfoils", to appear in NASA TM, 1990.

Hummel, D., "Zur Umstromung scharfkantiger schlanker Deltaflugel bei grossen Anstellwinkeln", Z. Flugwiss., Vol. 15, No. 10, 1967, pp. 376-385.

Hwang, C. and Pi, W.S., "Some Observations on the Mechanism of Aircraft Wing Rock", J. Aircraft, Vol. 16, No. 6, Jun. 1979, pp. 366-373.

Lamar, J.E., "Recent Studies of Subsonic Vortex Lift Including Parameters Affecting Stable Leading-Edge Vortex Flow", J. Aircraft, Vol. 14, No. 12, Dec. 1977, pp. 1205-1211.

Lamar, J.E. and Campbell, J.F., "Vortex Flaps-Advanced Control Devices for Supercruise Fighters", Aerospace America, Jan. 1984.

Lambourne, N.C. and Bryer, D.W., "The Bursting of Leading-Edge Vortices-Some Observations and Discussion of the Phenomenon", Aero. Res. Council, R M no. 3282, 1961.

Lambourne, N.C., Bryer, D.W. and Maybrey, J.F.M., "The Behaviour of the Leading-Edge Vortices over a Delta Wing Following a Sudden Change of Incidence", Aero. Res. Council, R M no. 3645, 1969.

Lee, G.H., "Note on the Flow Around Delta Wings with Sharp Leading Edges", Aero. Res. Council, R M No. 3070, 1955.

Lee, M., Shih, C. and Ho, C.M., "Response of a Delta Wing in Steady and Unsteady Flow", Proc. Forum on Unsteady Flow Separation, ASME 1987 Fluids Engineering Conference, Vol. 52, pp. 19-24.

Leibovich, S., "Vortex Stability and Breakdown: Survey and Extension", AIAA J., Vol. 22, No. 9, Sept. 1984, pp. 1192-1206.

Levin, D. and Katz, J., "Dynamic Load Measurements with Delta Wings Undergoing Self-Induced Roll Oscillations", J. Aircraft, Vol. 21, No. 1, Jan. 1984, pp. 30-36.

Maltby, R.L., Engler, P.B. and Keating, R.F.A., with addendum by Moss, G.F., "Some Exploratory Measurements by Leading Edge Vortex Positions on a Delta wing Oscillating in Heave", Aero. Res. Council, R M No. 3410, 1963.

Marchman, J.F., "Effects of Heating on Leading Edge Vortices in Subsonic Flow", J. Aircraft, Vol. 12, No. 12, Feb. 1975, pp. 121-123.

Marchman, J.F., "Aerodynamics of Inverted Leading-Edge Flaps on Delta Wings", J. Aircraft, Vol. 18, No. 12, Dec. 1981, pp. 1051-1056.

McKernan, J.F. and Nelson, R.C., " An Investigation of the Breakdown of the Leading Edge Vortices on a Delta Wing at High Angles of Attack", AIAA paper no. 83-2114, 1983.

Payne, F.M., "The Structure of Leading Edge Vortex Flows Including Vortex Breakdown", Ph.D. Dissertation, Dept. Aerospace and Mechanical Eng.,Univ. of Notre Dame, May 1987.

Payne, F.M., Ng, T.T., Nelson, R. C. and Schiff, L. B., " Visualization and Wake Surveys of Vortical Flow over a Delta Wing", AIAA J., Vol. 26, No. 1, Jan, 1988, pp. 137-143.

Parker, A.G., "Aerodynamic Characteristics of Slender Wings with Sharp Leading Edges-A Review", J. Aircraft, Vol. 13, No. 3, March 1976, pp. 161-168.

Patel, M.H., "The Delta Wing in Oscillatory Gusts", AIAA J., Vol. 18, No. 5, May 1980, pp 481-486.

Polhamus, E.C., "Predictions of Vortex-Lift Characteristics by a Leading-Edge-Suction Analogy", J. Aircraft, Vol. 8., No. 4, April 1971, pp .193-199.

Rao, D.M. and Buter, T.A., "Experimental and Computational Studies of a Delta Wing Apex-Flap", AIAA paper no. 83-1815.

Rao, D.M. and Johnson, T.D. Jr., "Investigation of Delta Wing Leading-Edge Devices", J. Aircraft, Vol. 18, No. 3, March 1981, pp. 161-167.

Reynolds, W.C. and Carr, L.W., "Review of Unsteady, Driven, Separated Flows", AIAA paper no.

85-0527.

Rizzetta, D.P. and Shang, J.S., "Numerical Simulation of Leading-Edge Vortex Flows", AIAA J., Vol. 24, Feb. 1986, pp. 237-245.

Rossow, V.J., "Lift Enhancement by an Externally Trapped Vortex", J. Aircraft, Vol. 15, No. 9, Sept. 1978, pp. 618-625.

Sforza, P.M., Stasi, W., Pazienza, W. and Smorto, M., " Flow Measurements in Leading-Edge Devices", AIAA J., Vol. 16, March 1978, pp. 218-224.

Shih, C.,"Unsteady Aerodynamics of a Stationary Airfoil in a Periodically-varying Free-stream", Ph.D thesis, University of Southern California, 1988.

Shih, C., Lee, M. and Ho, C.M., "Control of Separated Flow on a Symmetric Airfoil", Proc. of IUTAM Conf., Bangalore, India, Jan. 1987.

Spedding, G.R., Maxworthy, T. and Rignot, E., "Unsteady Vortex Flows over Delta Wings", Proc. 2nd. AFOSR Workshop on Unsteady and Separated Flows, Colorado Springs, Colorado, July 1987.

Stanbrook, A, and Squire, L.C., "Possible Types of Flow at Swept Leading Edges", Aeronautical Quarterly, Vol. XV, 1964, pp. 72-82.

Squire, L.C., "Flow Regimes over Delta Wings at Supersonic and Hypersonic Speeds", Aeronautical Quarterly, Vol. XXVII, 1976, pp. 1-14.

Squire, L.C., Jones, J.G. and Stanbrook, A., "An Experimental Investigation of the Characteristics of some Plane and Cambered 65° Delta Wings at Mach Numbers from 0.7 to 2.0", Aero. Res. Council, R M No. 3305, 1961.

Trebble, W.J.G., "Exploratory Investigation of the Effects of Blowing from the Leading Edge of a Delta Wing", Aero. Res. Council, R M No. 3518, 1966.

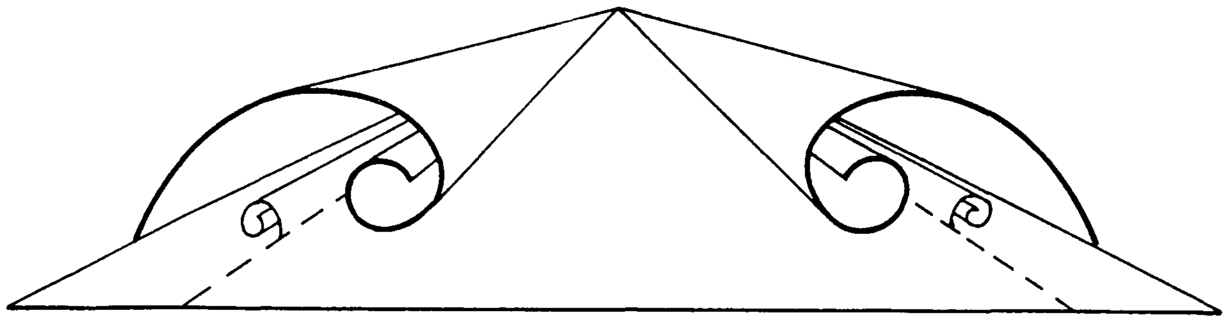
Wahls, R.A., Vess, R.J. and Moskovitz, C.A., "Experimental Investigation of Apex Fence Flaps on Delta Wings", J. Aircraft, Vol. 23, No. 10, Oct. 1986, pp. 789-797.

Wedemeyer, E., "Vortex Breakdown", AGARD/VKI Lecture Series No.121, March 1982. Wentz., W.H. Jr., "Effects of Leading Edge Camber on Low Speed Characteristics of Slender Delta Wings", NASA CR-2002, Oct. 1972.

Wentz, W.H. and Kohlman, D.L., "Vortex Breakdown on Slender Sharp-Edged Wings", J. Aircraft, Vol. 8, No. 3, March 1971, pp. 156-161.

Wood, R.M. and Miller, D.S., "Fundamental Aerodynamic Characteristics of Delta Wings with Leading-Edge Vortex Flows", J. Aircraft, Vol. 22, No. 6, June 1985, pp. 479-485.

Wood, N.J. and Roberts, L., "The Control of Vortical Lift on Delta Wings by Tangential Leading Edge Blowing", AIAA paper No.87-0158.



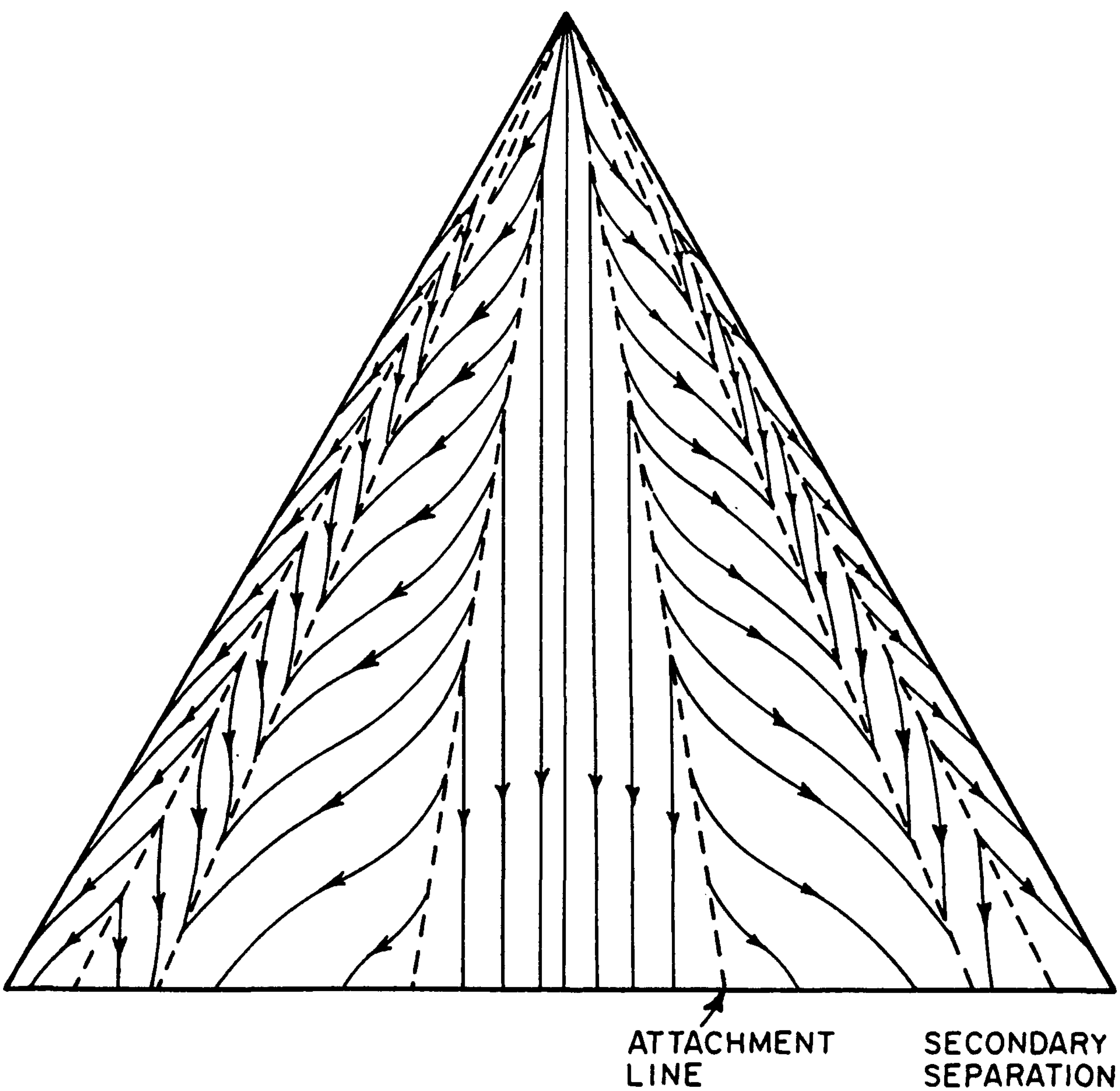


Fig. 1: [a] Leading edge vortices and [b] Surface flow pattern, Earnshaw and Lawford [1964]

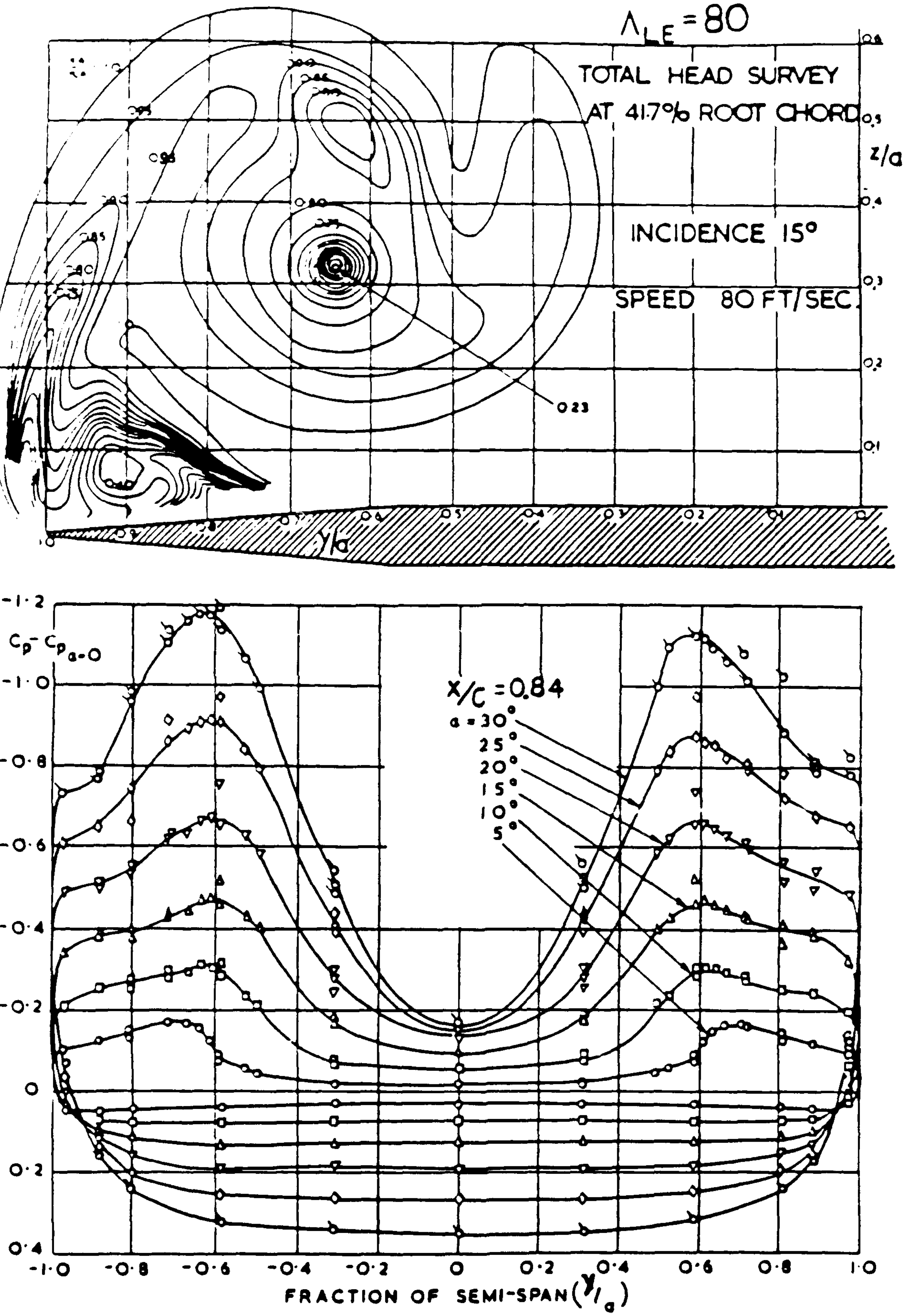


Fig. 2: [a] Total head measurement of the L. E. vortices
[b] Surface pressure measurements, Fink and Taylor [1967]

Fig. 3: Secondary vortices superimposed on L. E. separation vortices, Payne [1987]

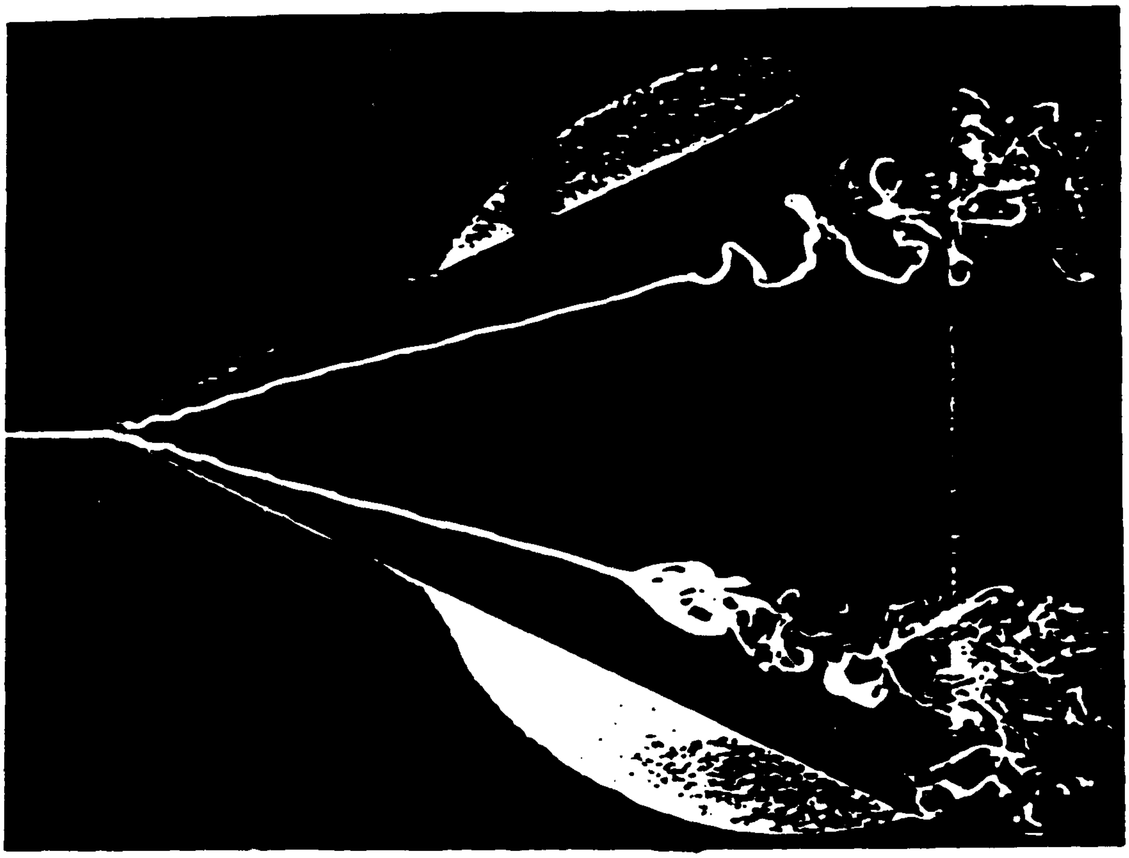


Fig. 4: Patterns of vortex breakdown, Lambourne and Bryer [1961]

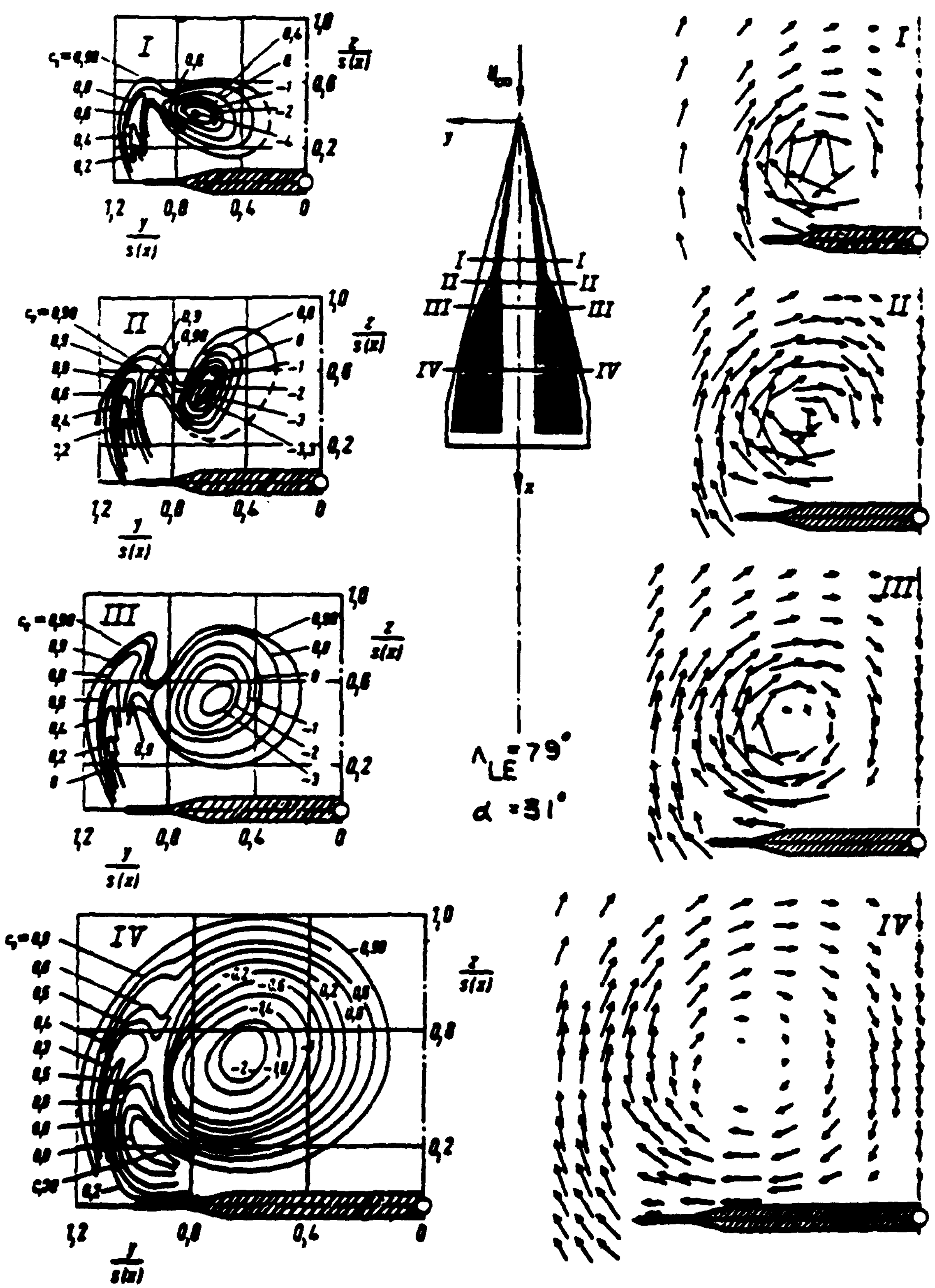


Fig. 5: Velocity distributions before and after vortex breakdown, Hummel [1965]

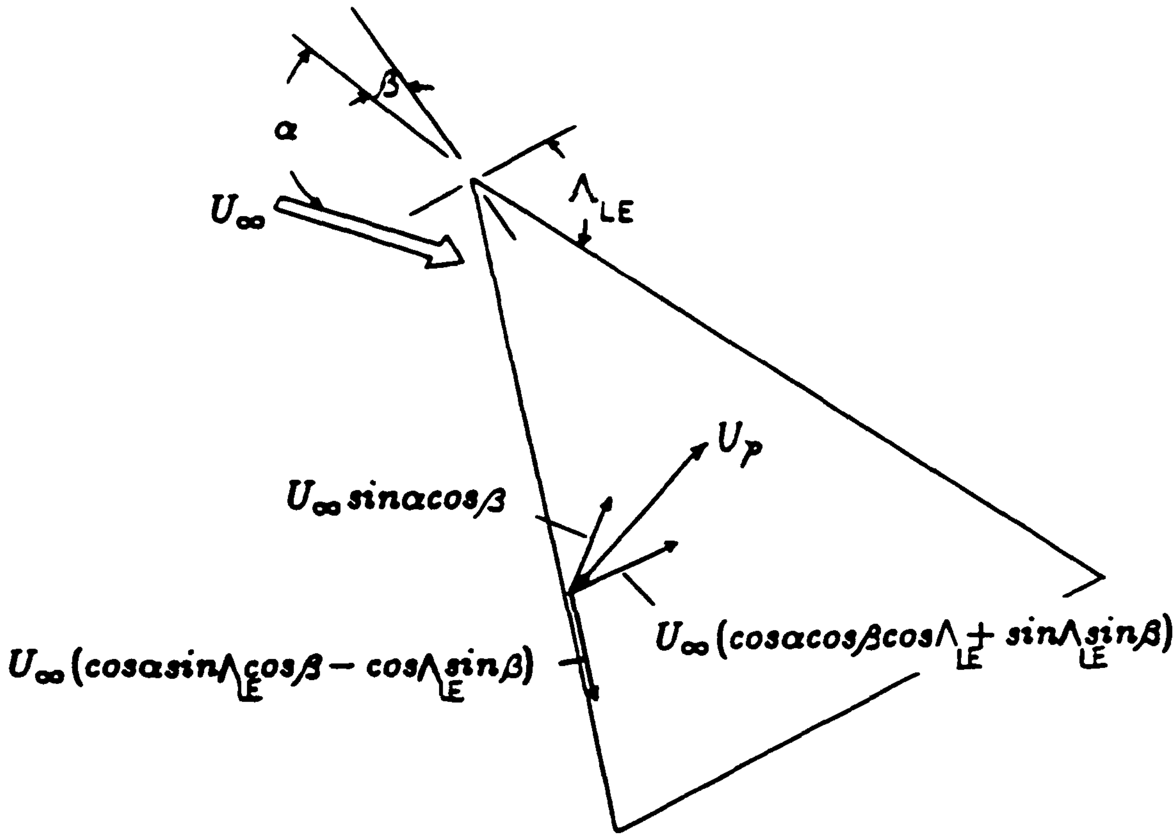


Fig. 6: Geometric relation of velocity and delta wing

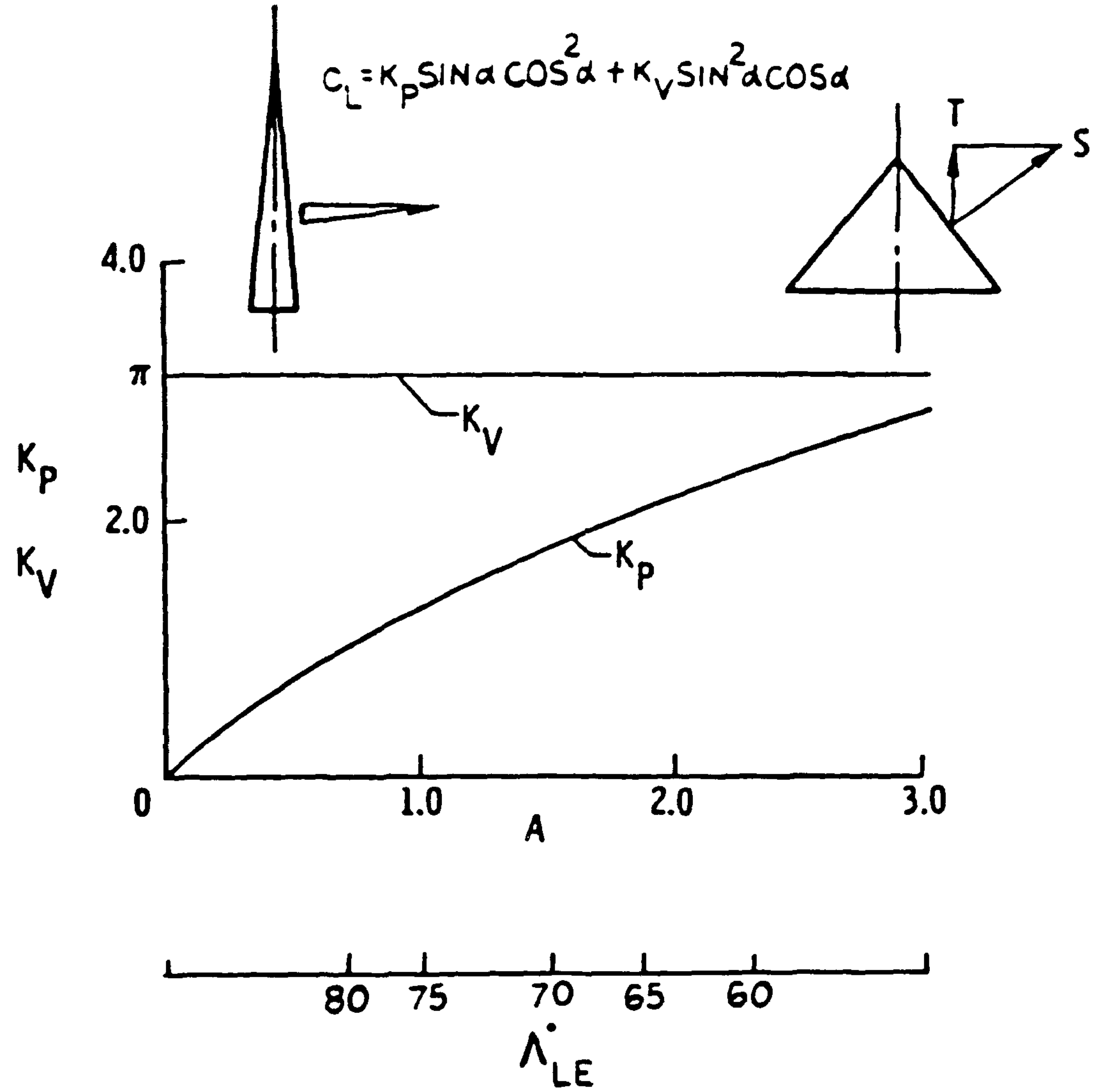
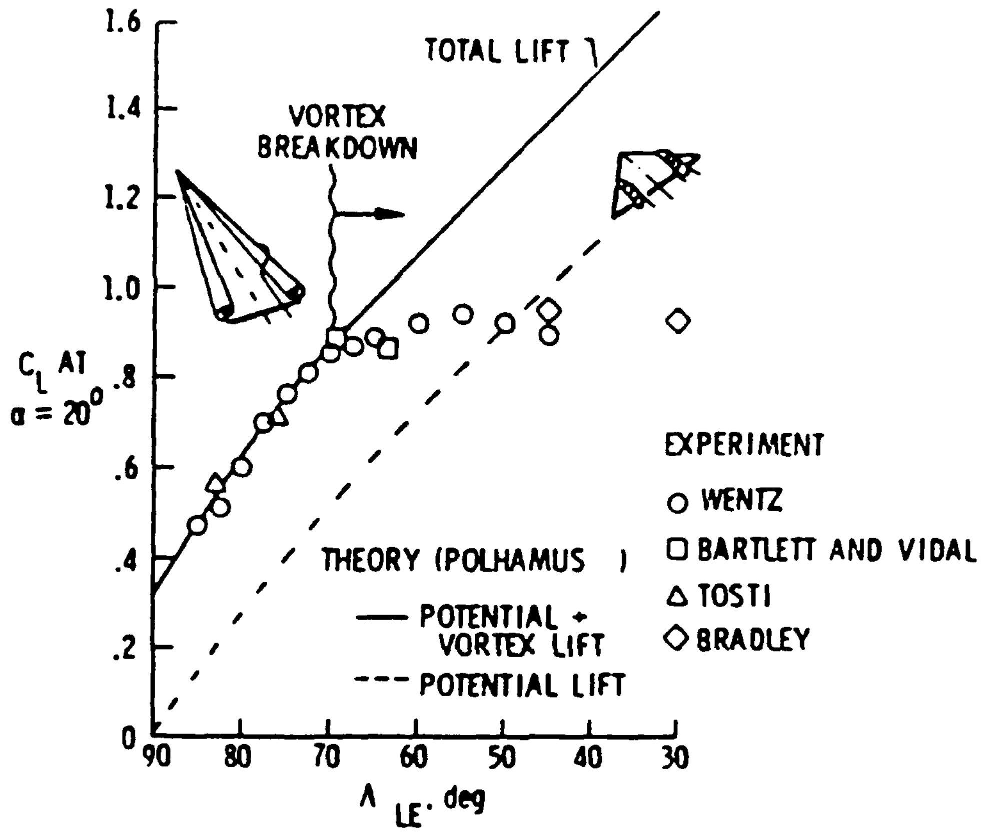


Fig. 7: Vortex and potential lift, Polhamus [1971]



Lift capability of delta wings at $\alpha = 20°$.

Fig. 8: Vortex breakdown and the leading edge suction analogy, Campbell [1976]

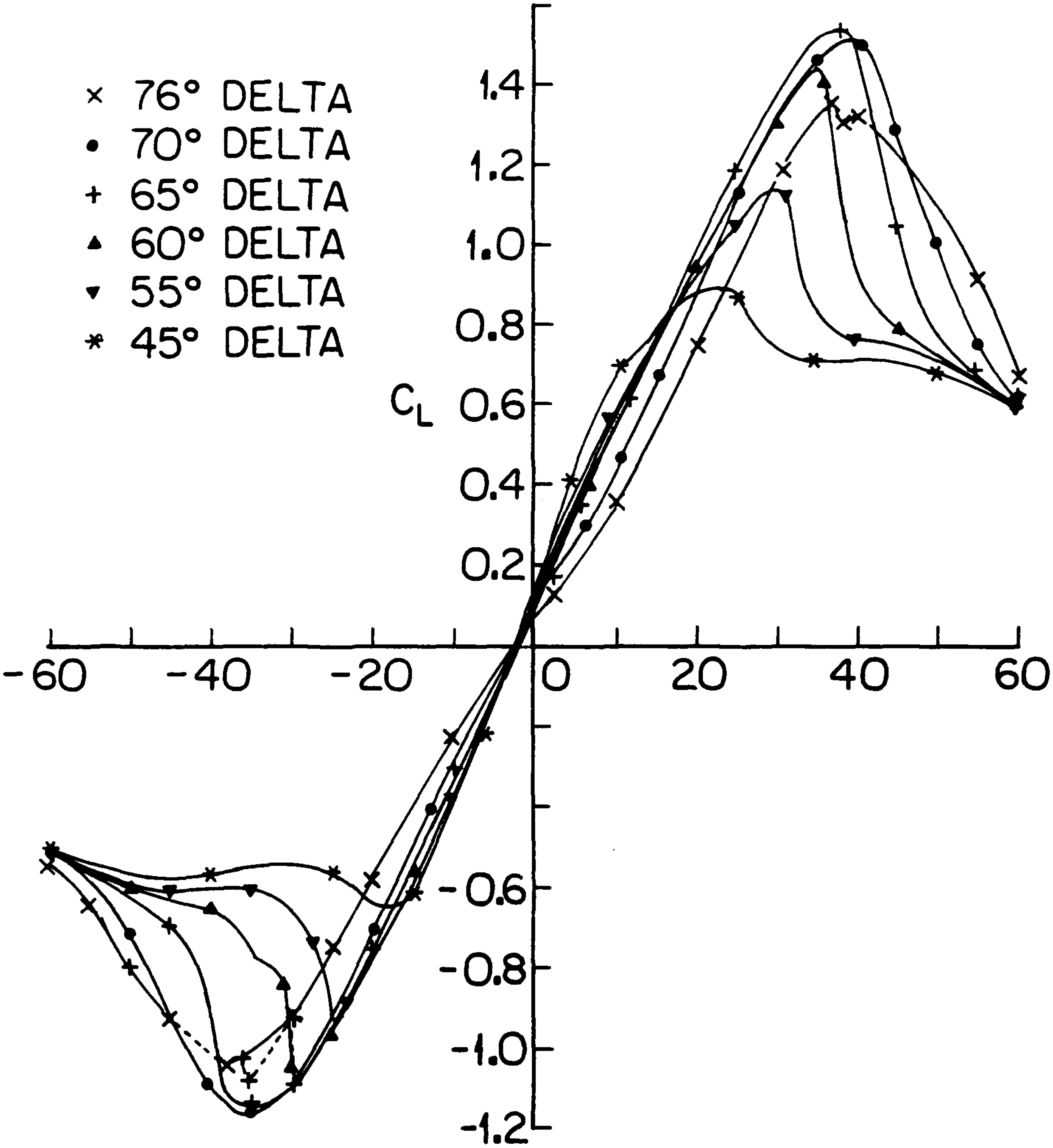
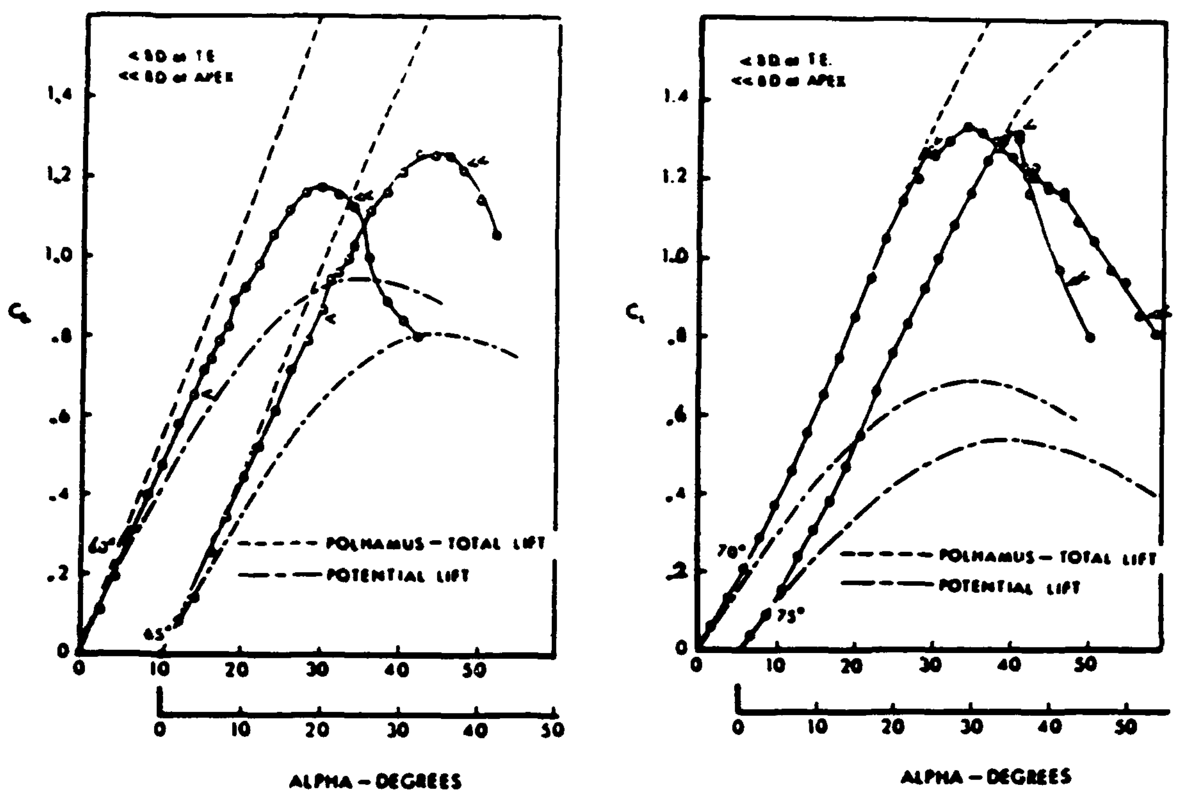


Fig. 9: Lift coefficient vs angle of attack, Earnshaw and Lawford [1964]



a) 60° and 65° delta wings

b) 70° and 75° delta wings

Fig.10: Comparison between experiments and Polhamus' prediction, Wentz and Kohlman [1971]

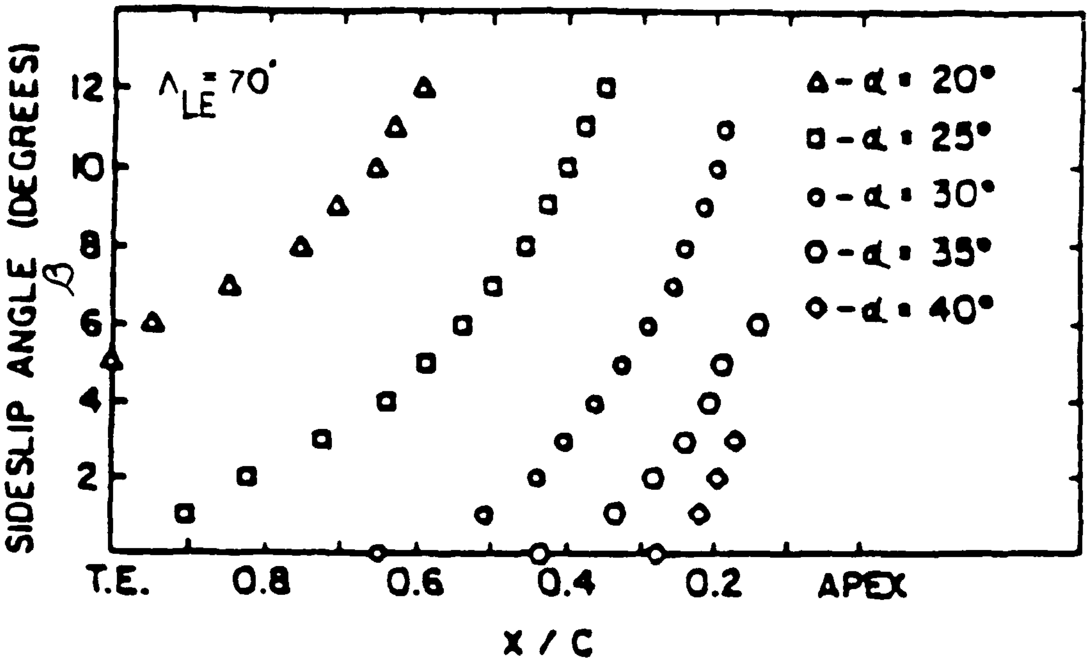


Fig.11: Effect of yaw on the vortex breakdown position, Mckernan and Nelson [1983]

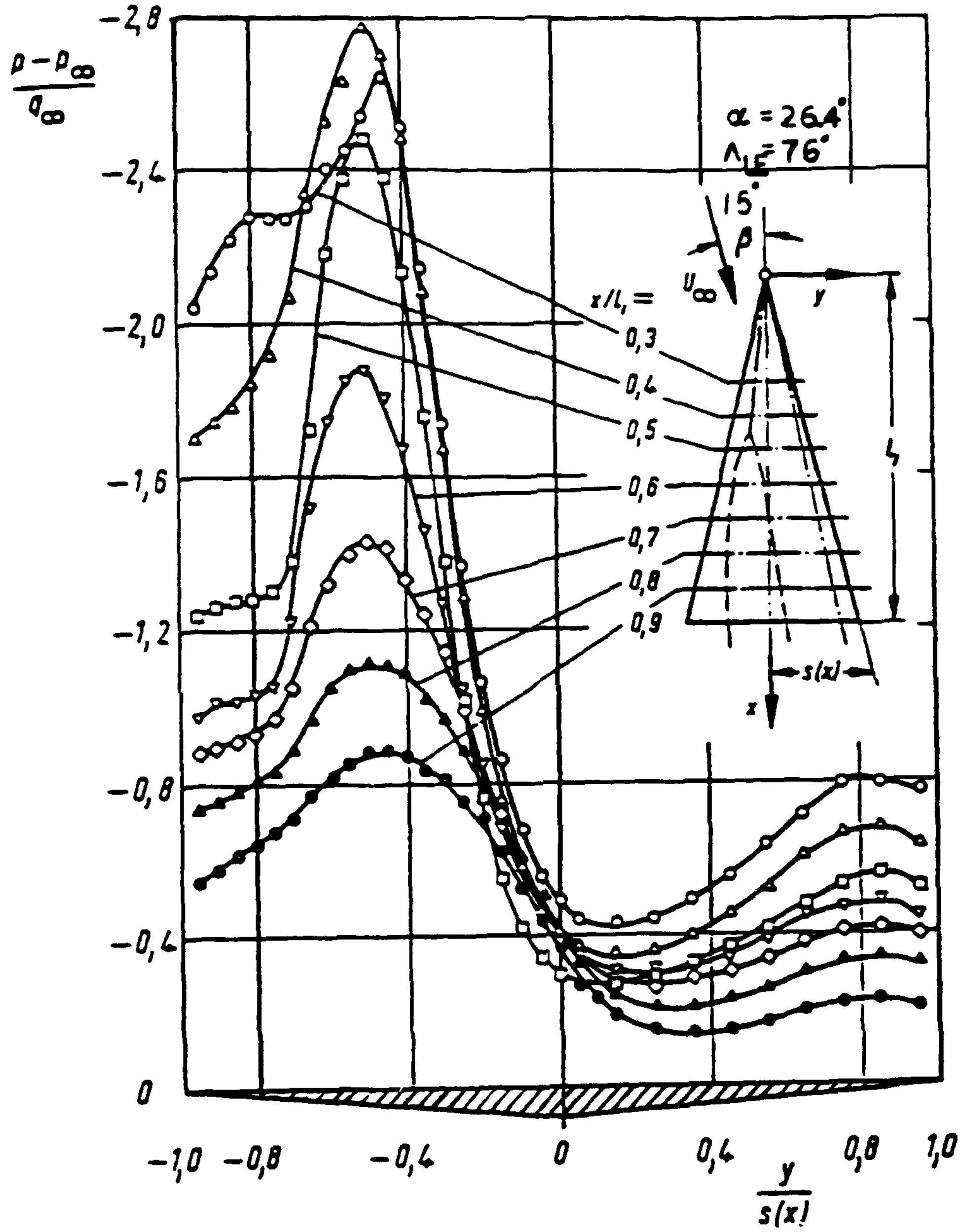
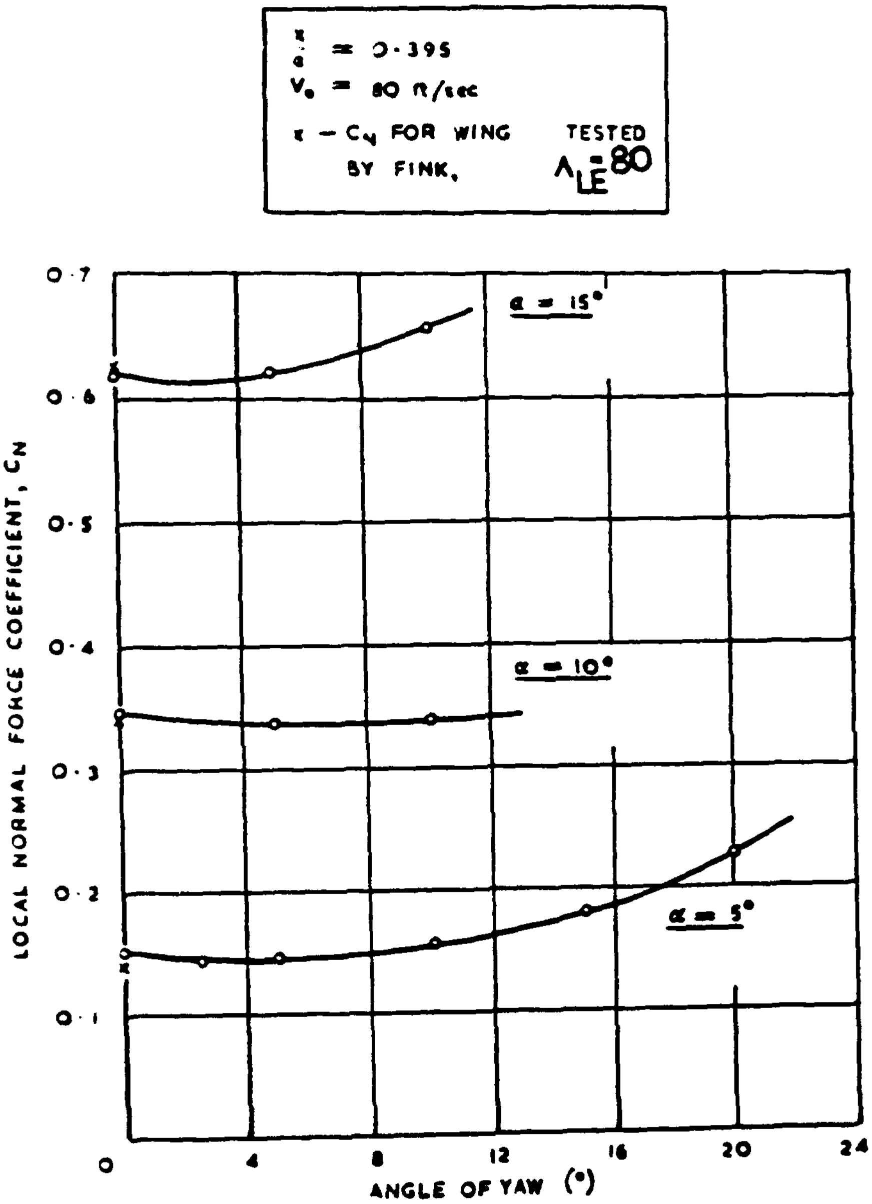


Fig.12: Suface pressure measurement of a yawed delta wing, Hummel [1965]



The normal force acting on the wing.

Fig.13: Normal force of a yawed delta wing, Harvey [1958]

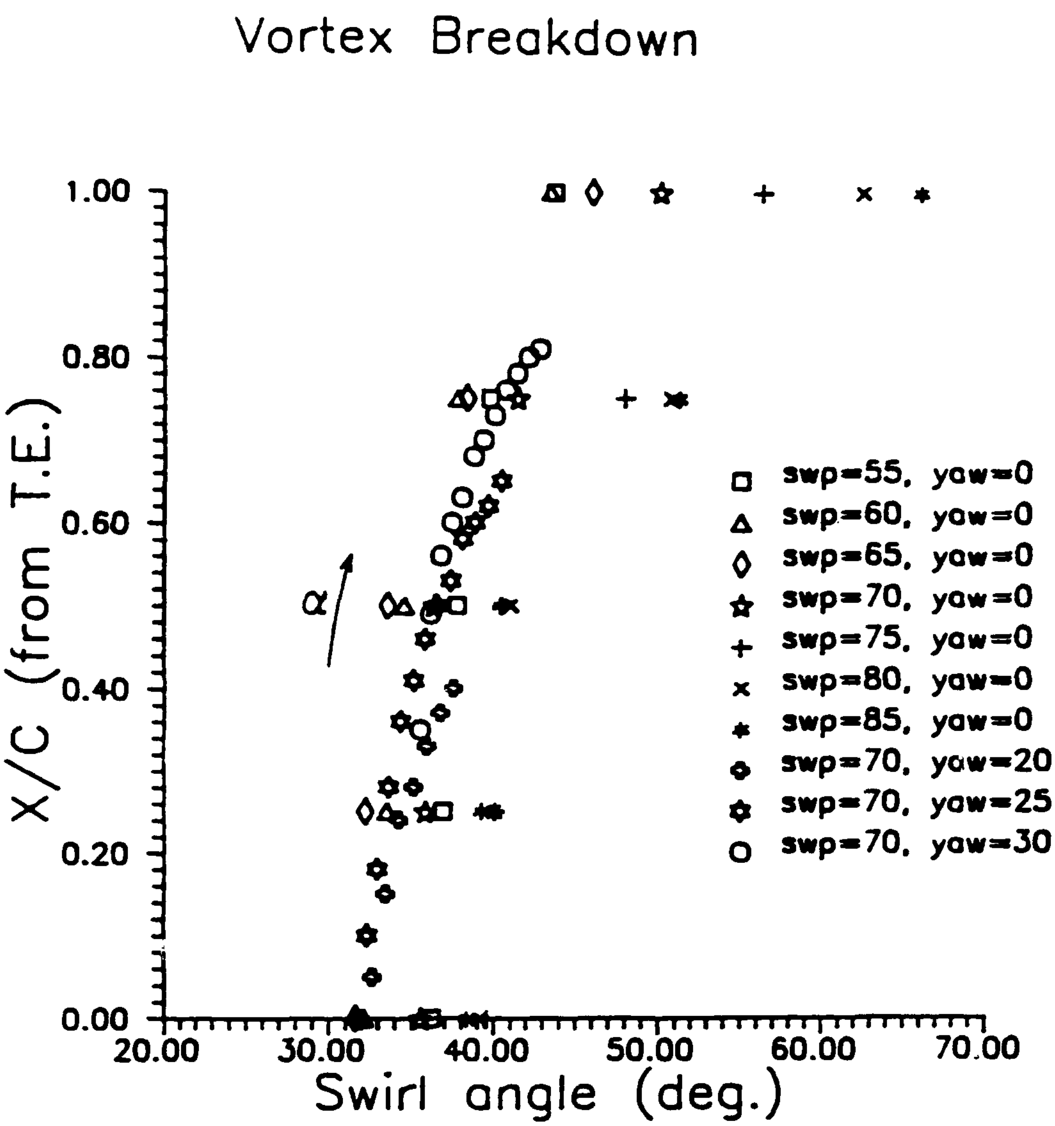


Fig.14: A scaling law of the vortex breakdown positions

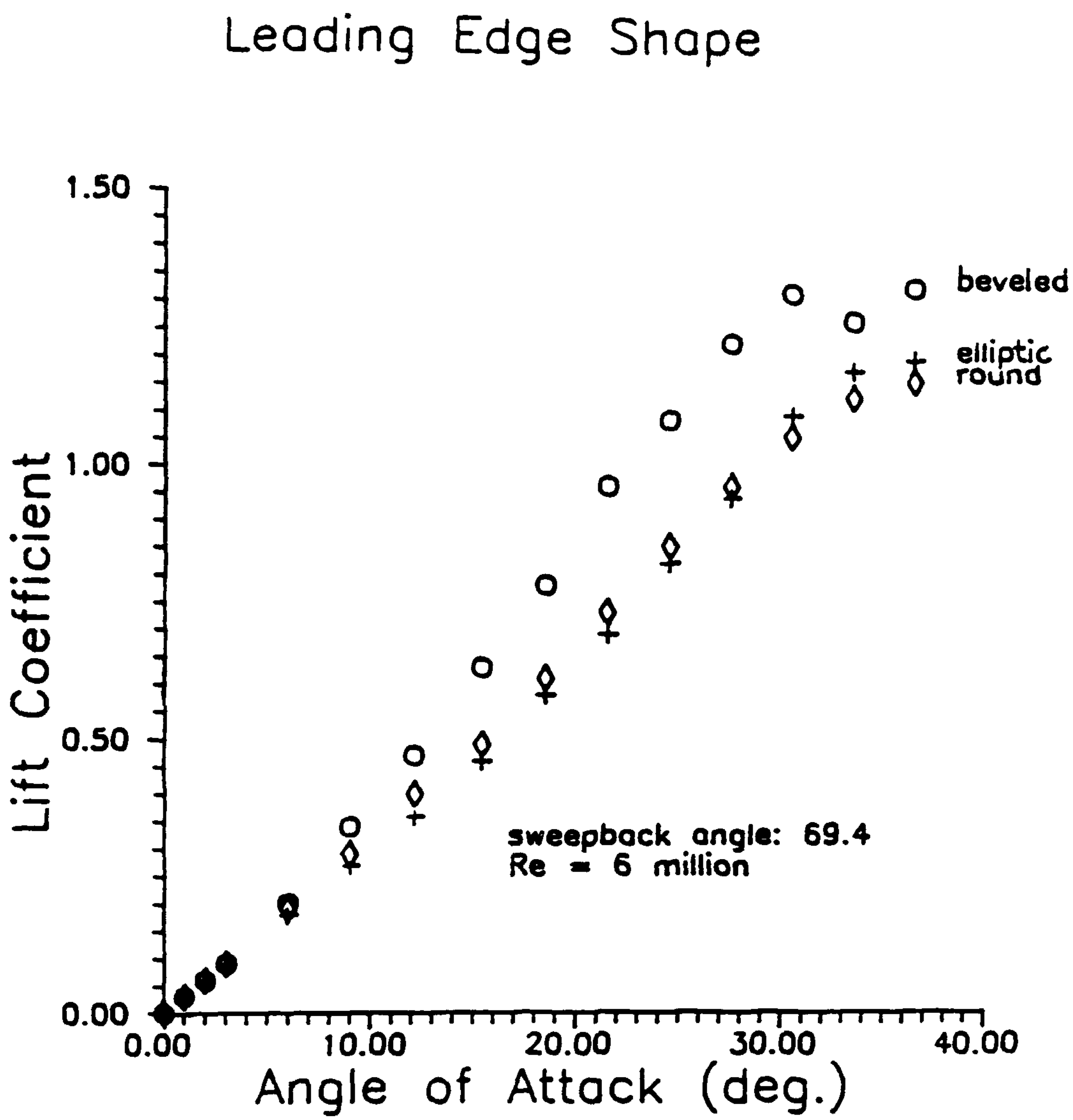
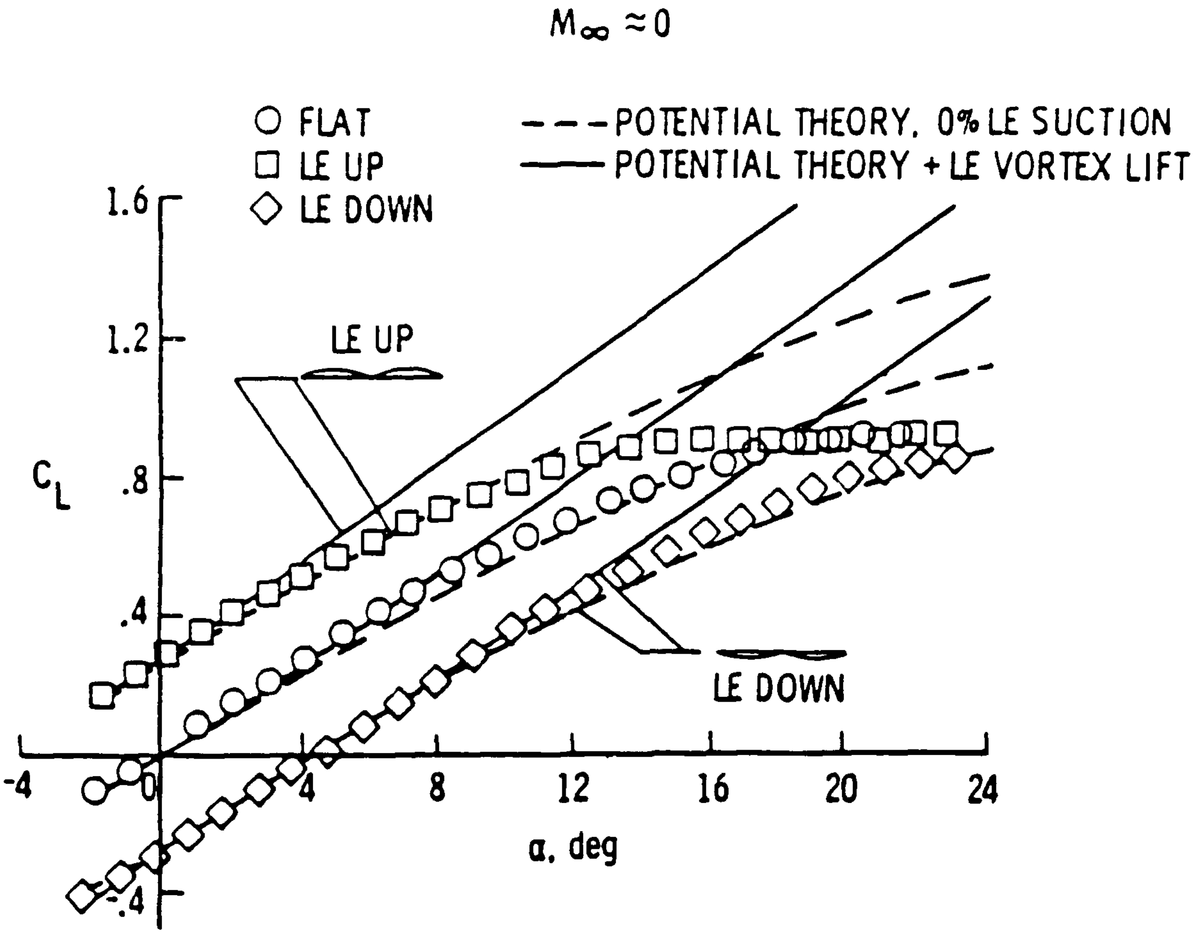


Fig.15: Effect of leading edge profile on the lift coefficient, Barlet and Vidal [1955]



Lift characteristics for 45-deg delta wing, flat and linearly twisted ("bat wing"), $M_\infty \approx 0$.

Fig.16: Lift coefficient of linearly twisted wings, Lamar[1977]

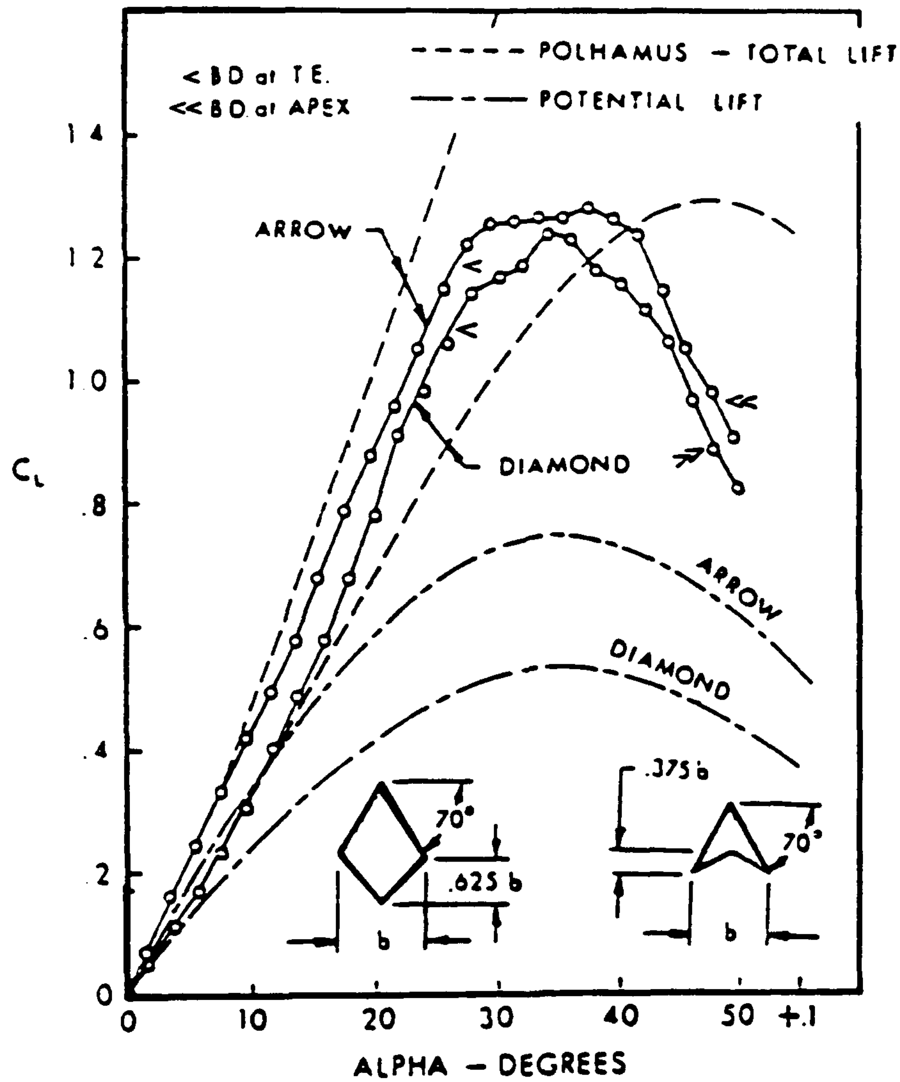
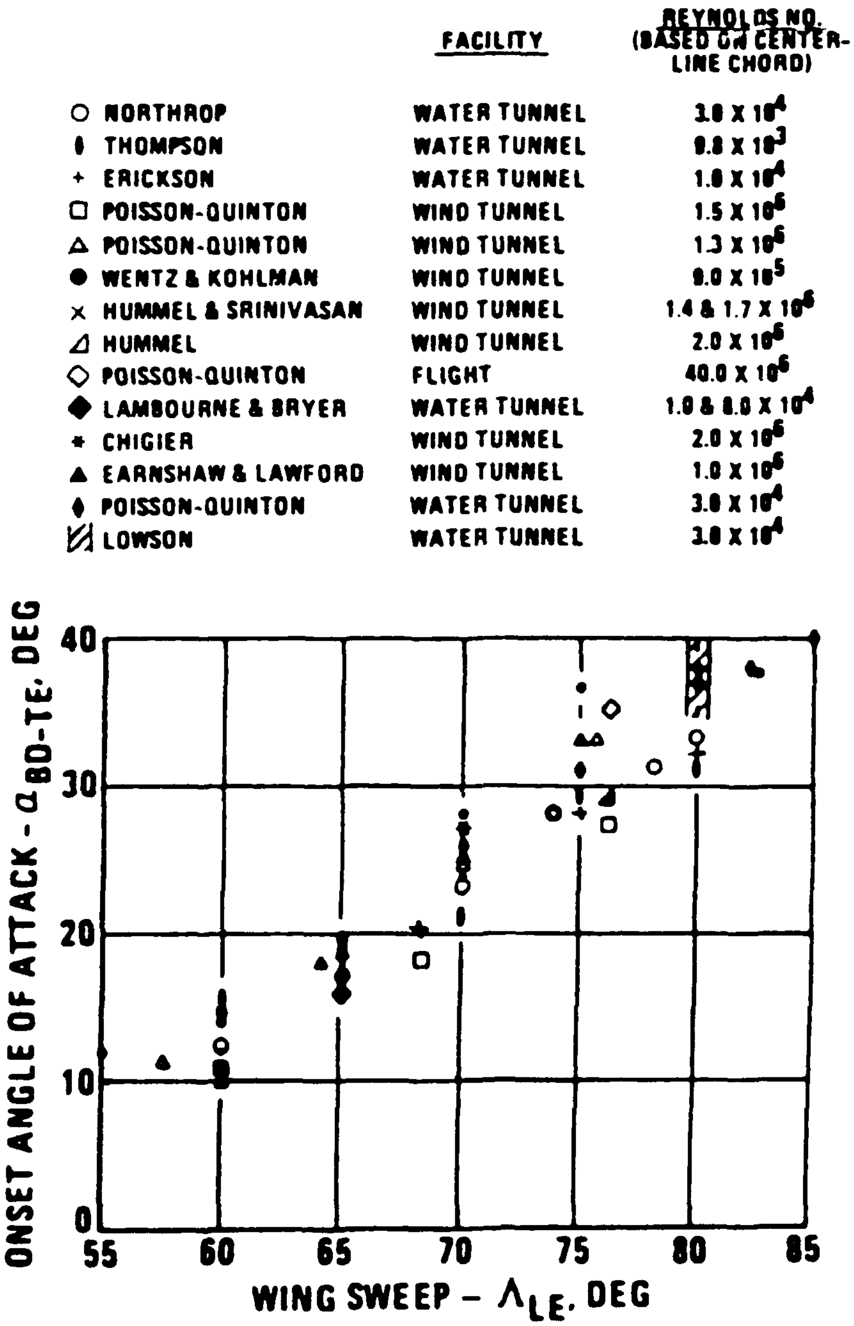
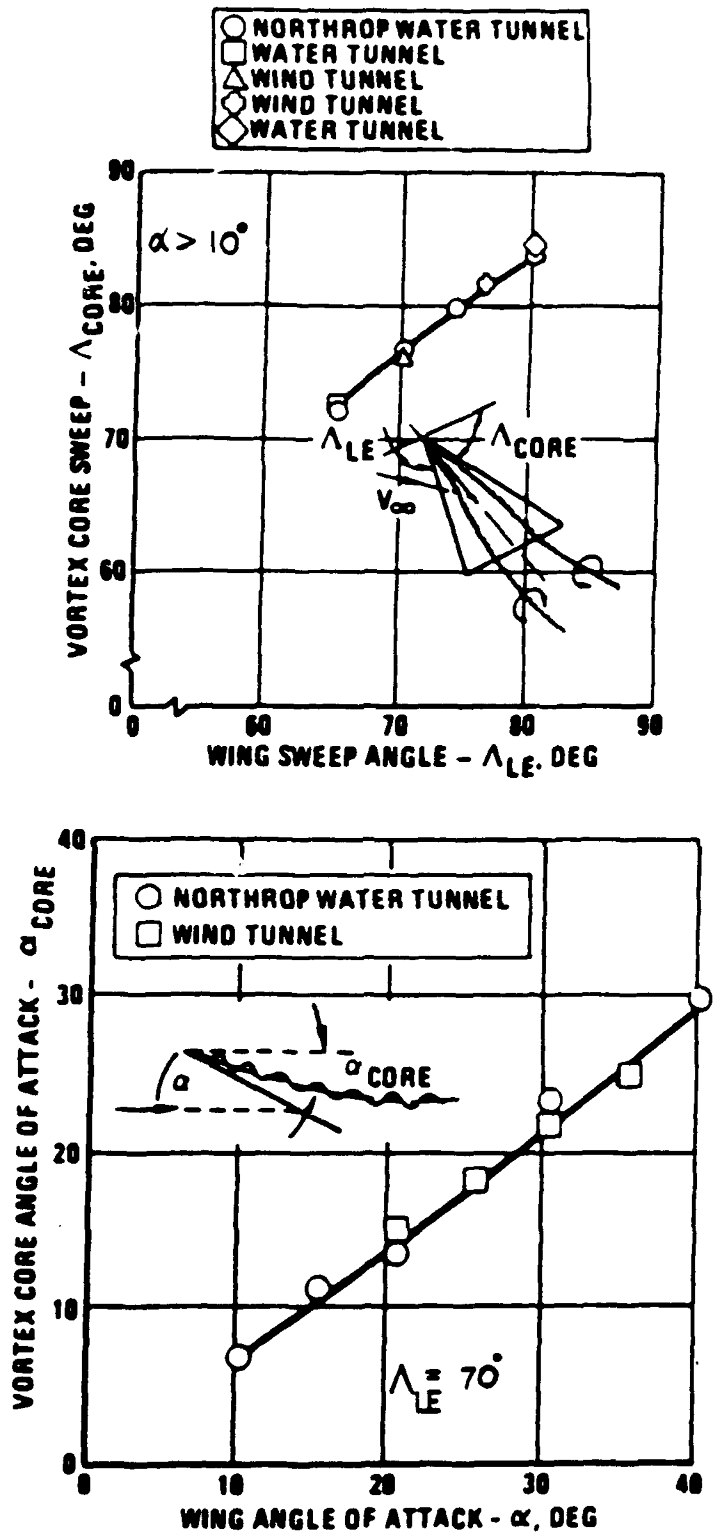


Fig.17: Trailing edge geometry ane its effects on lift, Wentz and Kolman [1971]



(A)

Fig.18: Effects of Reynolds number on the vortex breakdown and vortex positions, Ericksson [1982]


NORTHROP WATER TUNNEL
WATER TUNNEL
WIND TUNNEL
WIND TUNNEL
WATER TUNNEL
VORTEX CORE SWEEP – Λ_{CORE}, DEG
WING SWEEP ANGLE – Λ_{LE}, DEG
$\alpha > 10°$
Λ_{LE}
Λ_{CORE}
V_∞
NORTHROP WATER TUNNEL
WIND TUNNEL
VORTEX CORE ANGLE OF ATTACK - α_{CORE}
WING ANGLE OF ATTACK - α, DEG
α_{CORE}
$\Lambda_{LE} = 70°$

(B)

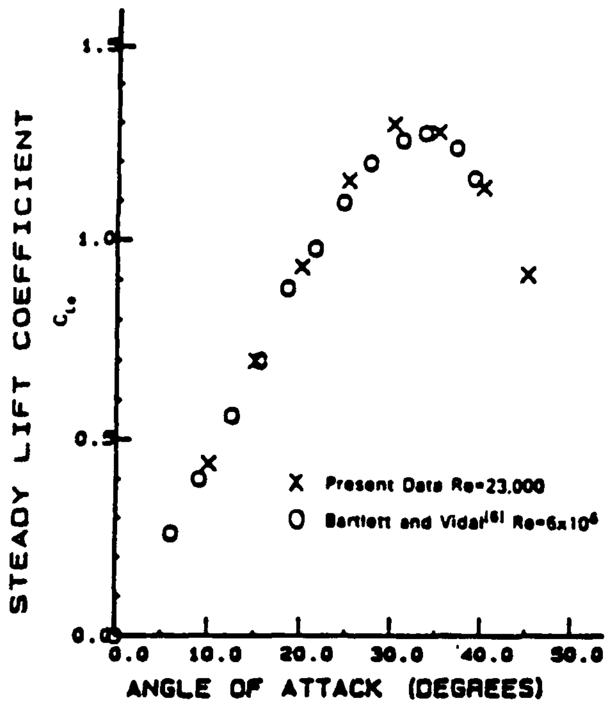


Fig.19: Effects of Reynolds number on lift coefficient,
Lee, Shih and Ho [1987]

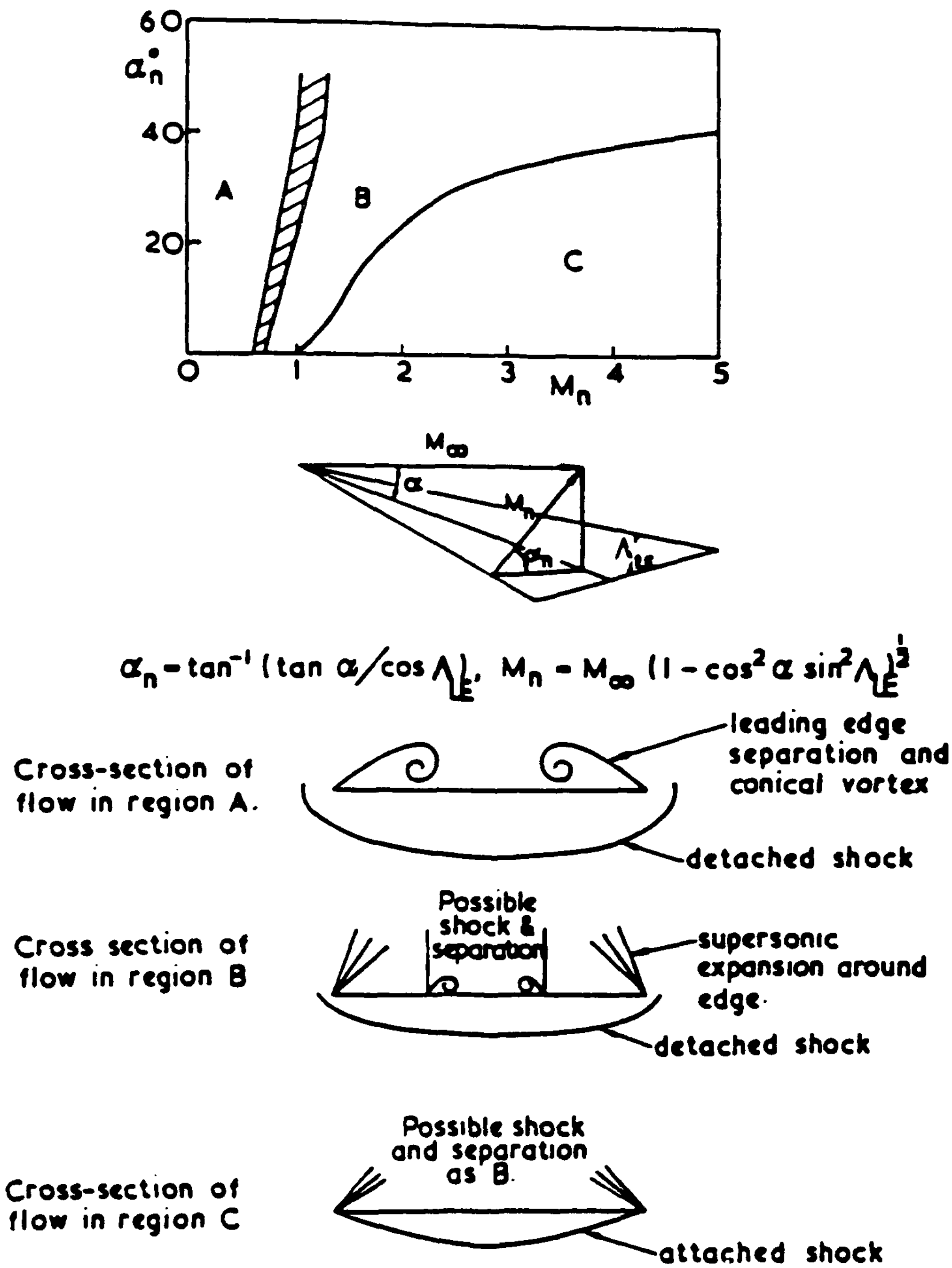
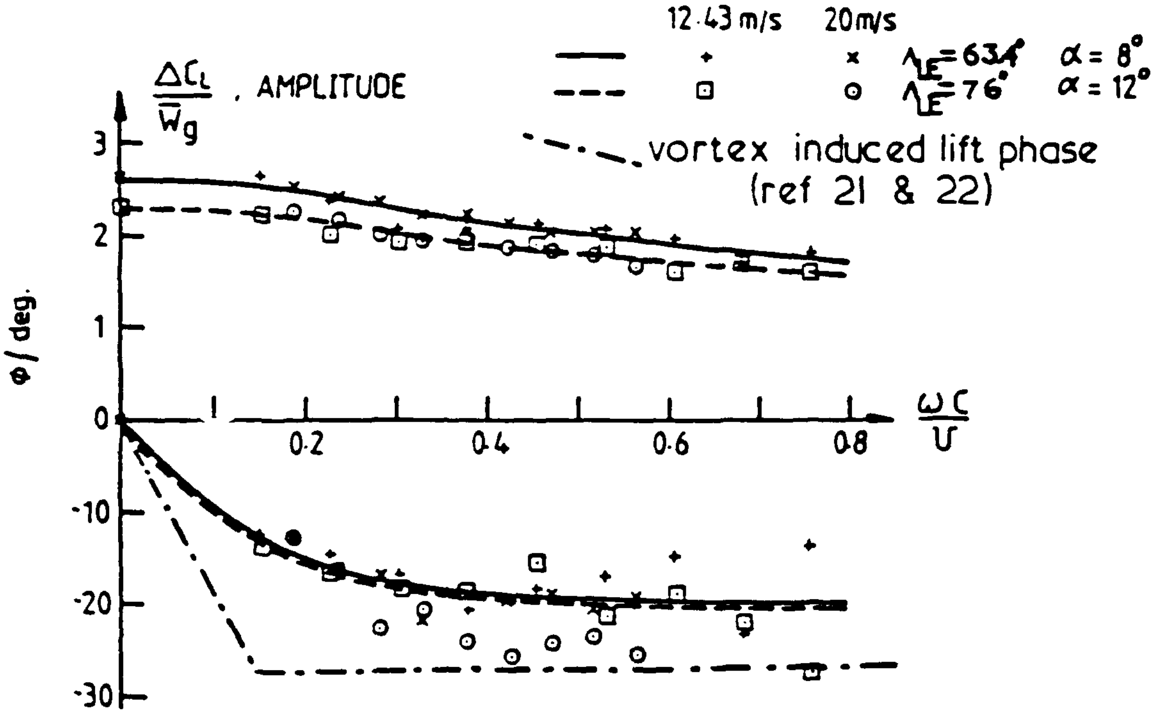
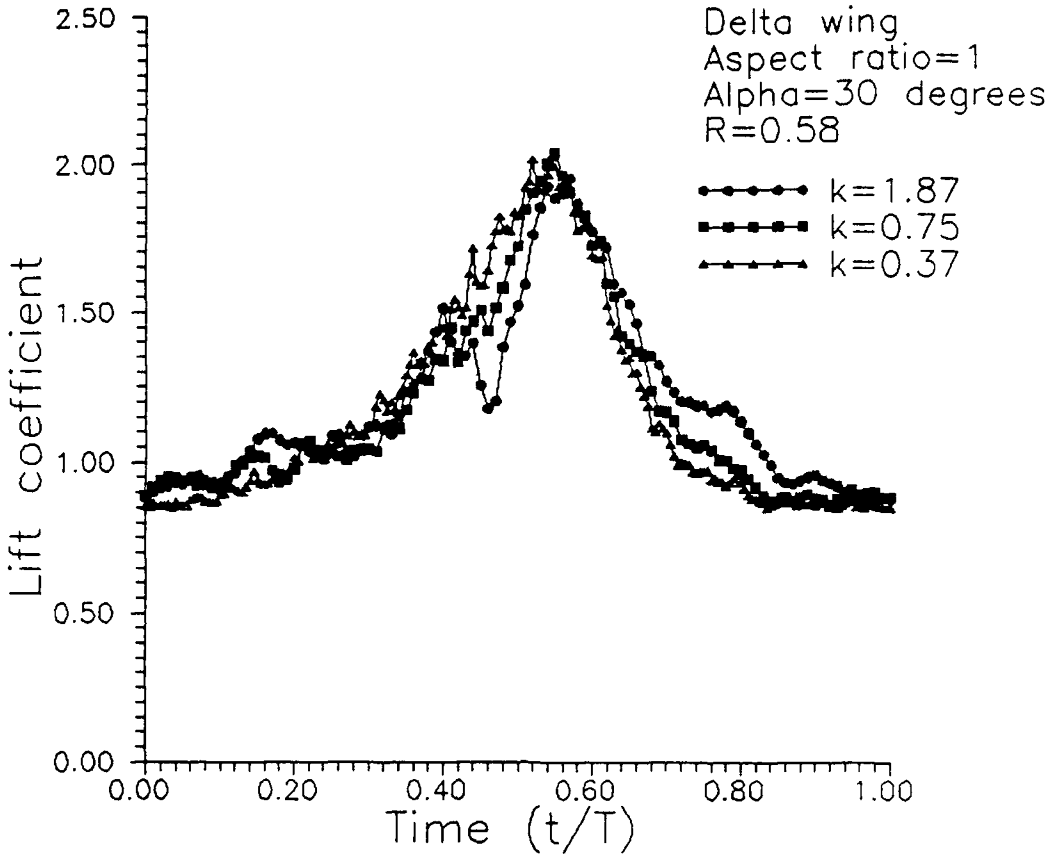


Fig.20: Flow field of a supersonic delta wing, Squire [1976]



Oscillatory lift forces at high incidences.

Fig.21: Amplitude and phase angle of lift coefficient as the function of gust frequency, Patel [1980]



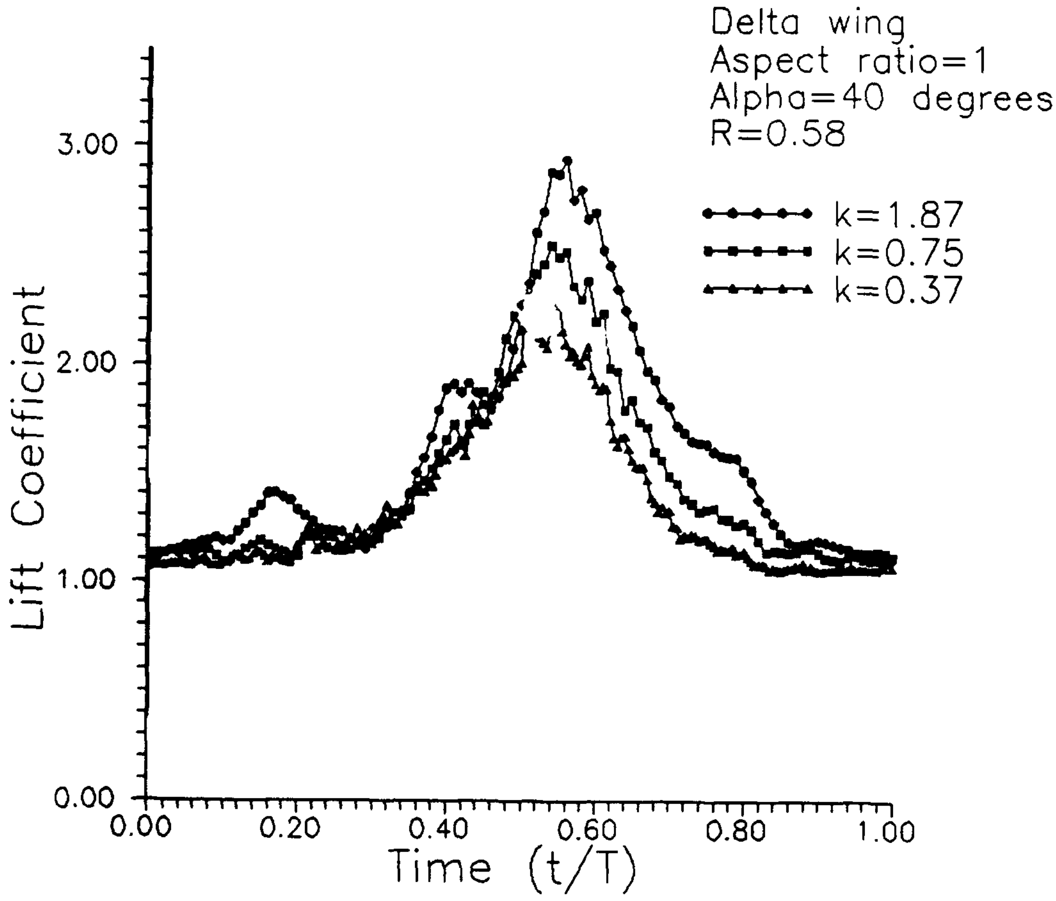
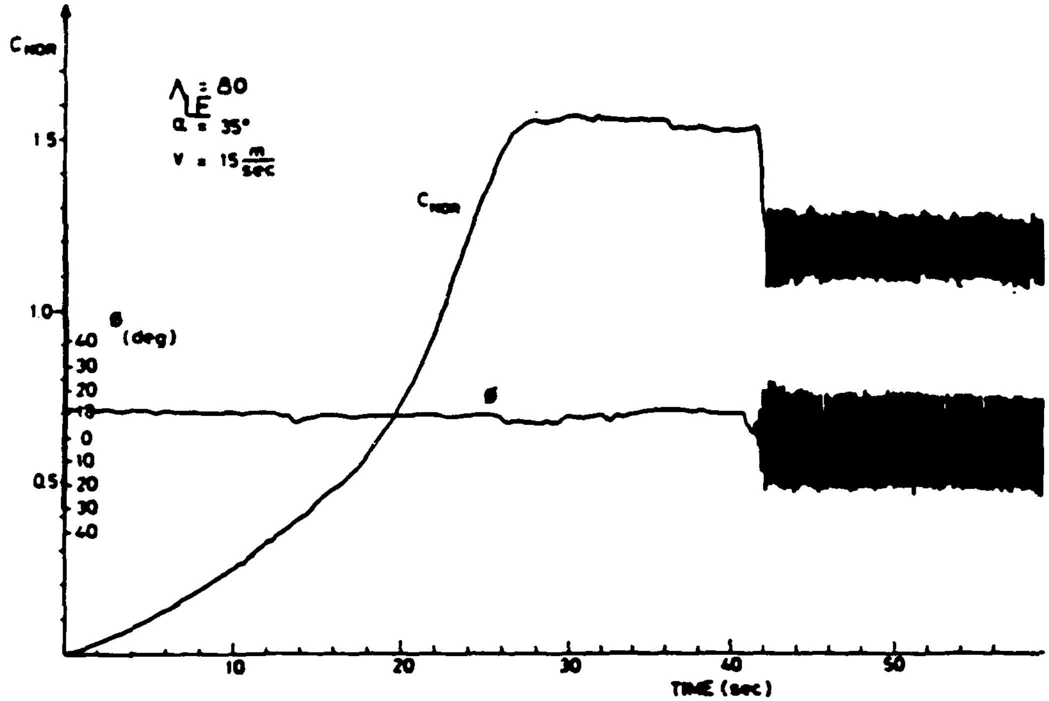


Fig.22: Unsteady lift coefficient, Ho, C. M., Gursel, I., Shih, C., and Lin H. (1990)
(a) Cases for stationary leading-edge vortices
(b) Cases for convecting leading-edge vortices



Development of "wing rock."

Fig.23: Time history of normal force and roll angle at the onset of wing rocking, katz [1984]

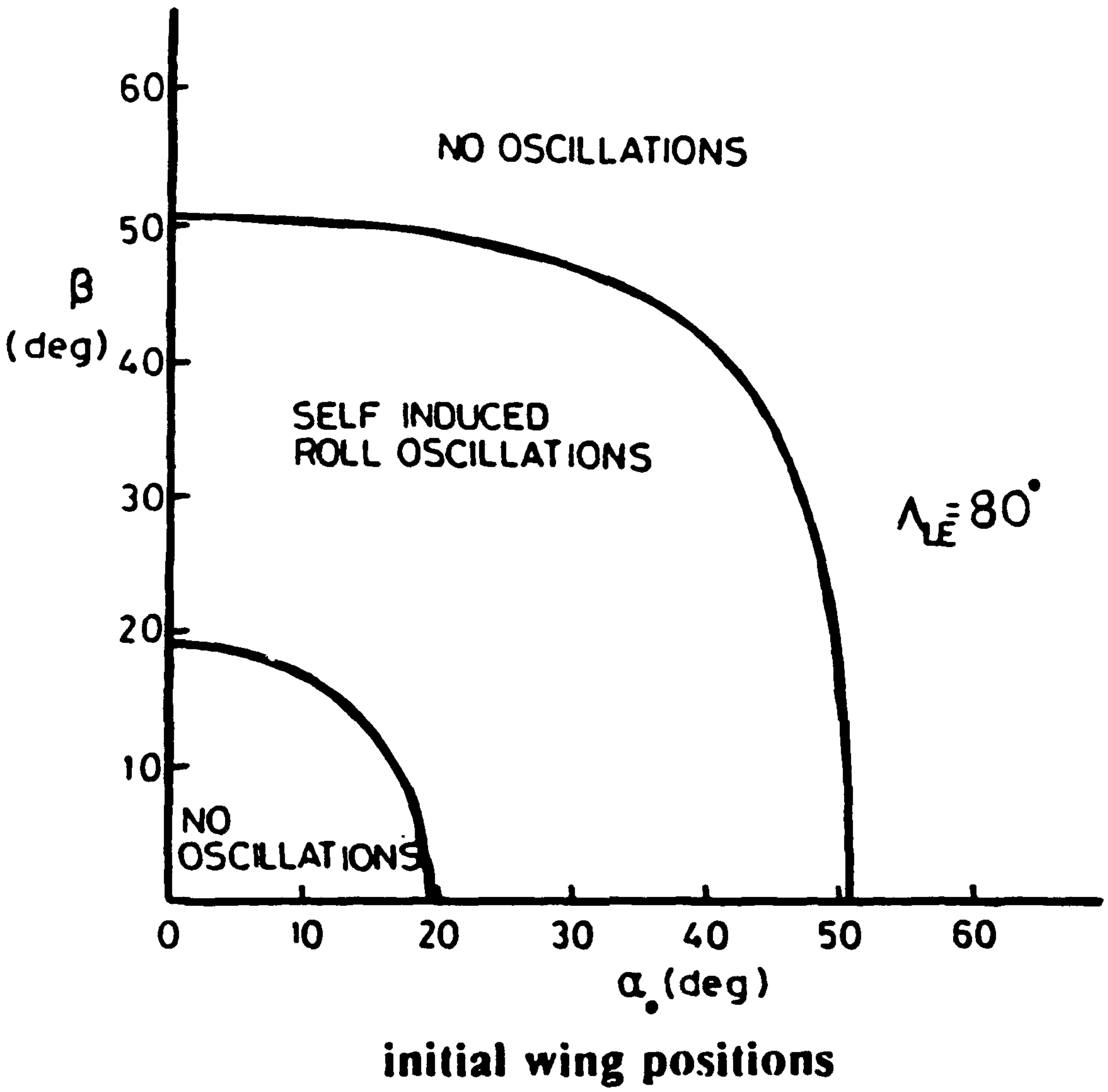


Fig.24: Wing rocking as a function of its initail condition, Katz [1984]

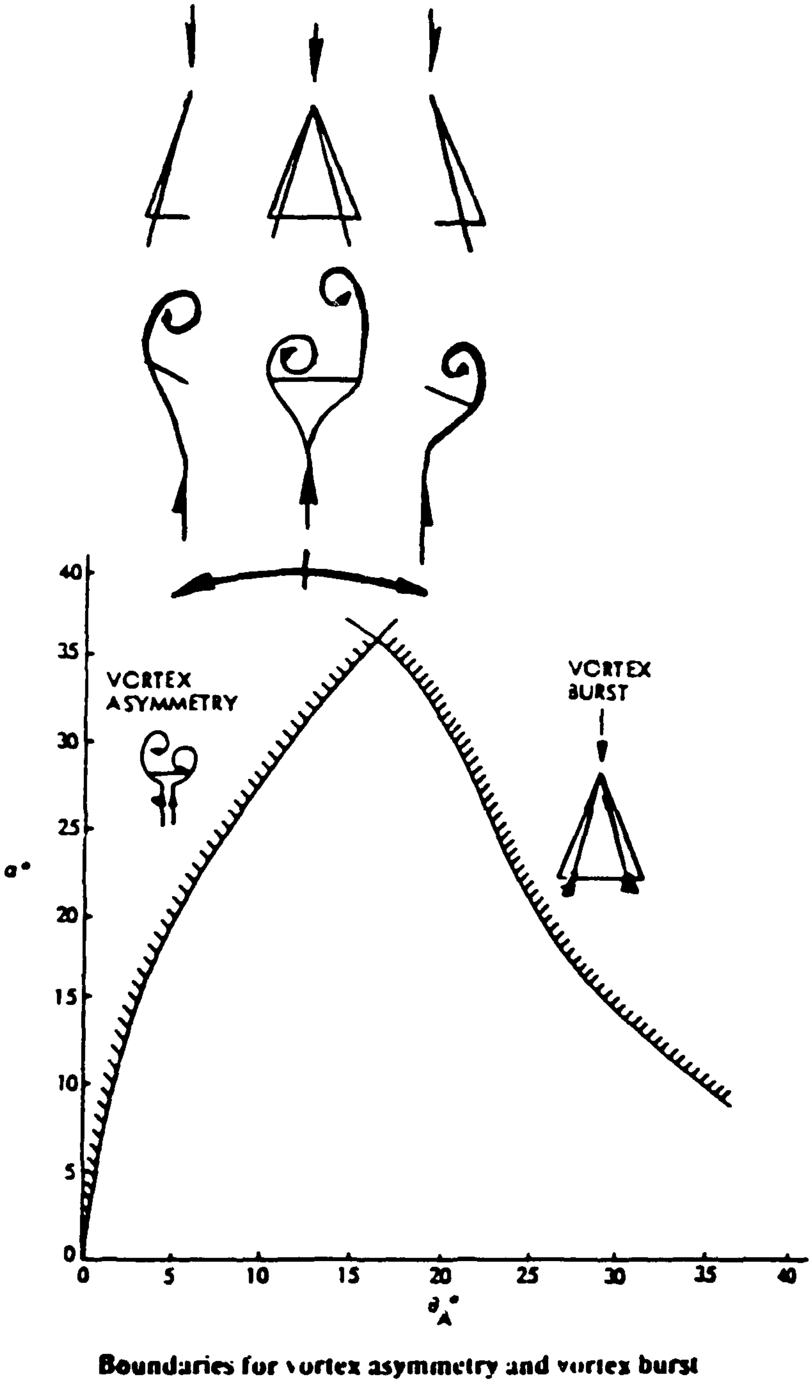


Fig.25: Boundaries for vortex asymmetry and vortex burst, Ericsson [1984]

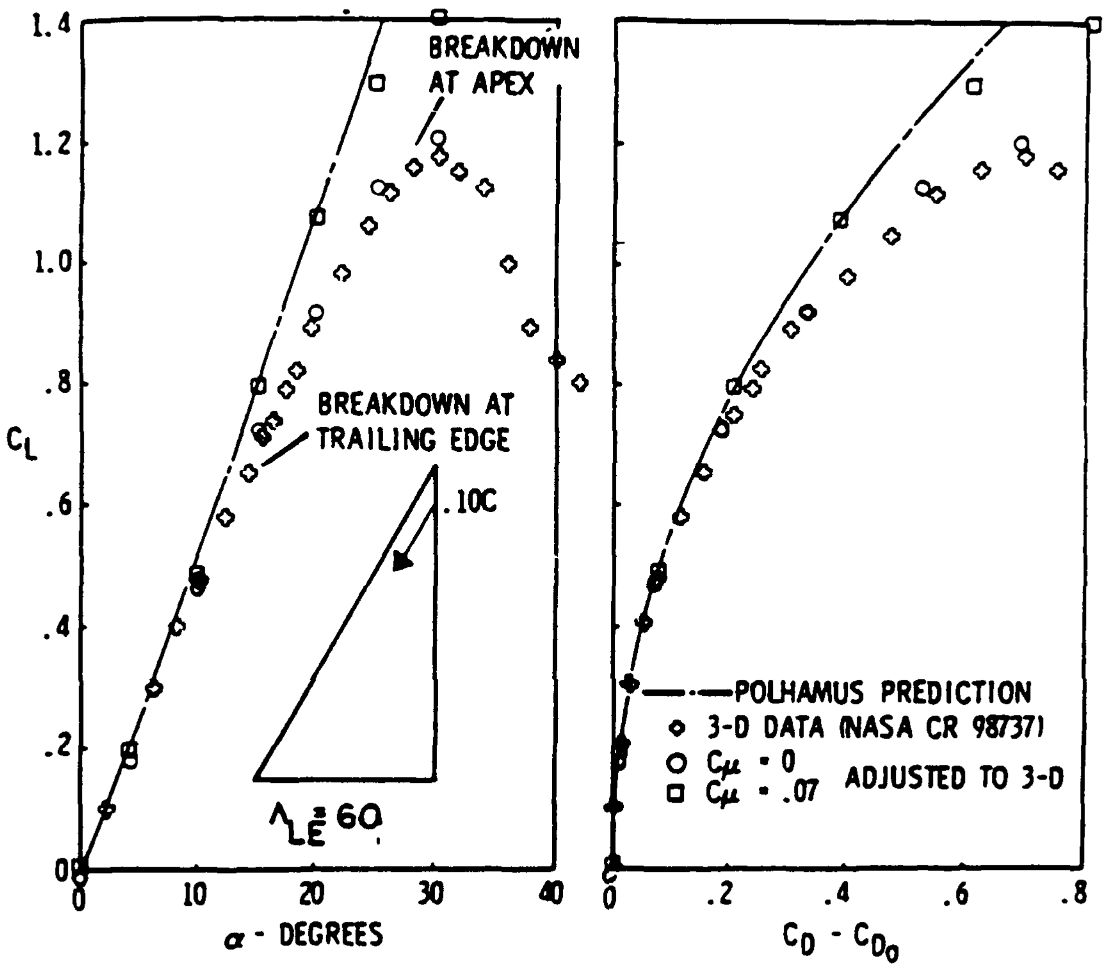


Fig.26: Measurements of lift coefficient with axial blowing, Bradley and Wray [1974]

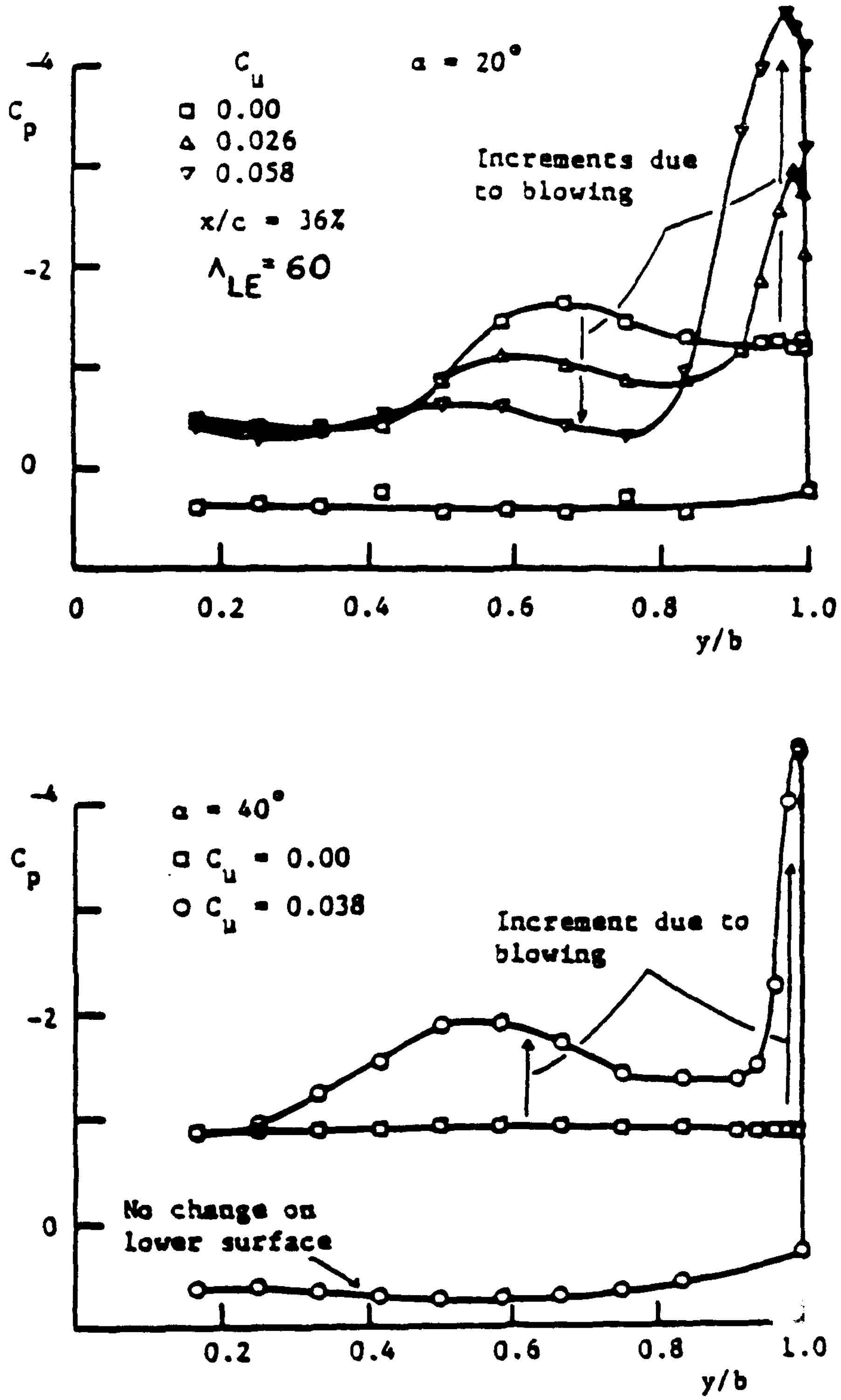


Fig.27: Pressure distribution of delta wing with tangential blowing, Roberts [1987]

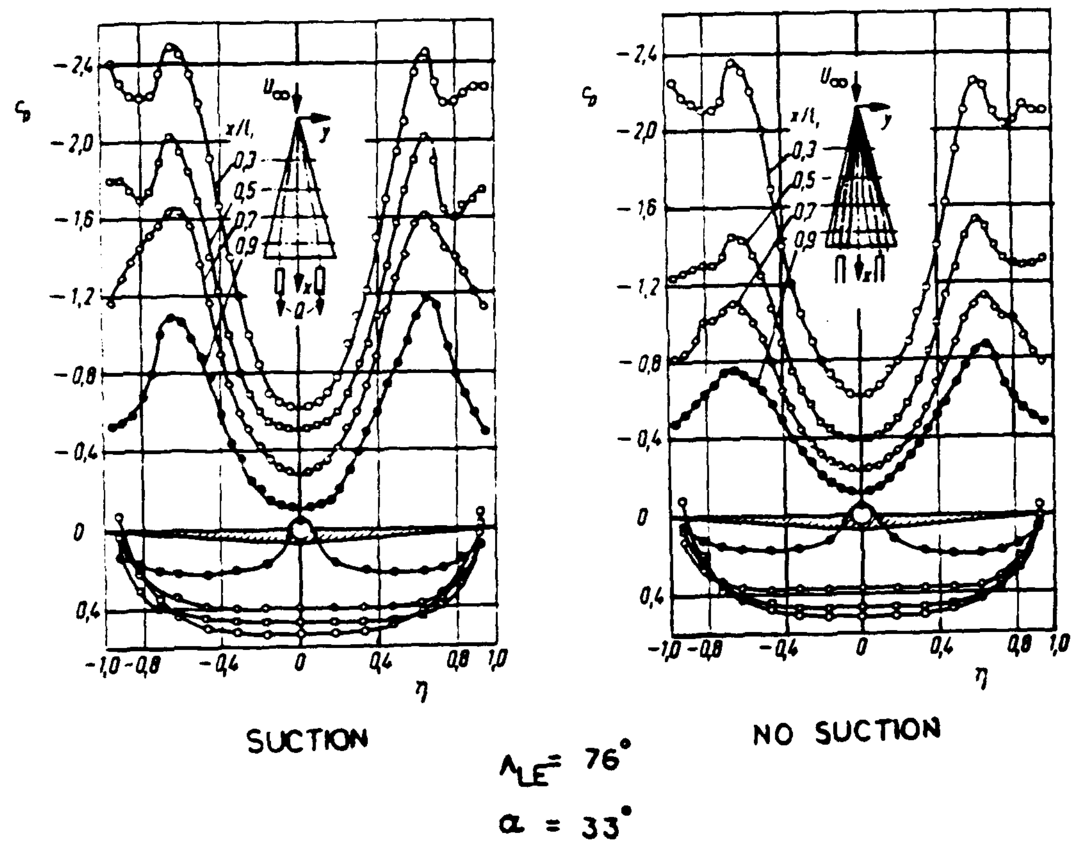


Fig.28: Surface presure distribution with trailing edge suction, Hummel [1967]

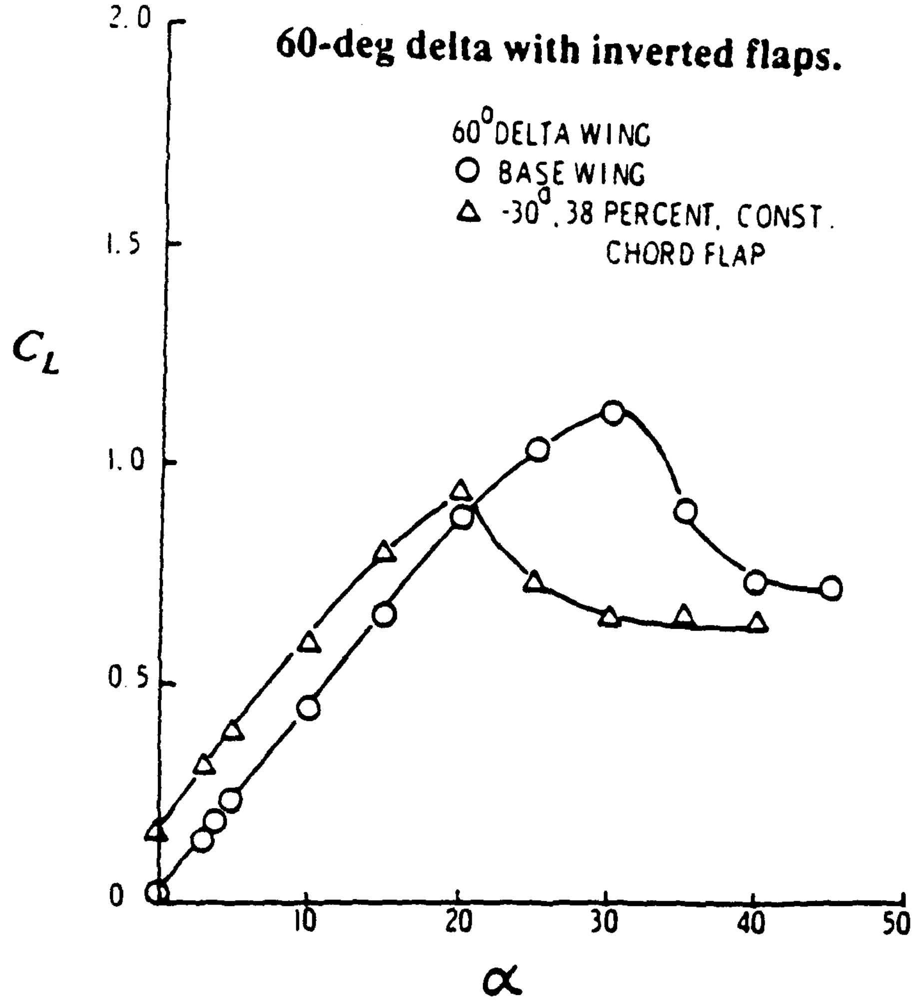
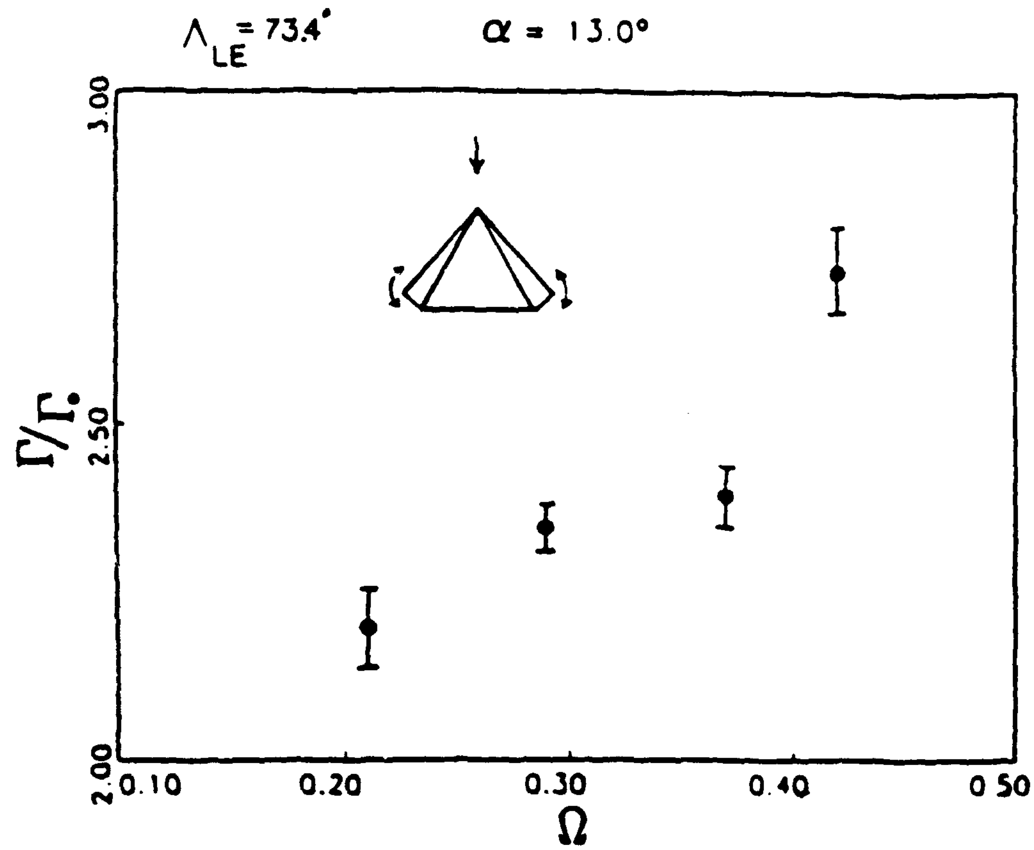


Fig.29: Lift coefficient of a wing with steady inverted flaps, Marchman [1981]



The change in normalised circulation with reduced frequency for a flap in continuous sinusoidal oscillation. The measurements were taken at the maximum flap opening angle. $\delta_{max} = 70°$.

Fig.30: Changes in circulation by unsteady flap, Spedding, Maxworthy and Rignot [1987]